AFML-TR-68-114

DEVELOPMENT OF A MANUFACTURING PROCESS AND ASSOCIATED EQUIPMENT TO IMPROVE INTERNAL CORE FORMING IN SOLID PROPELLANT ROCKET MOTORS

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TECHNICAL REPORT AFML-TR-68-114

May 1968

Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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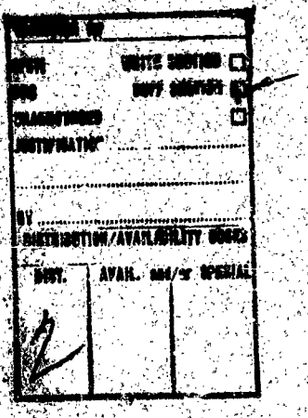

FOREWORD

This Final Technical Report covers the work performed under Contract AF33(615)-2998 and Modifications S/A 1, 2, and 3 from 15 July 1965 to 1 June 1968. Technical effort in Phase I was conducted during the period 15 July 1965 to 17 August 1966, while work in Phases II and III was accomplished during the period July 1967 to March 1968. No work was performed from August 1966 to July 1967 pending redirection of the contract from the Air Force.

This contract with the Huntsville Division of Thiokol Chemical Corporation, Huntsville, Alabama, was initiated under Manufacturing Technology Division Project No. 8-260, "Program to Develop a Manufacturing Process and Associated Equipment to Improve Internal Core Forming in Solid Propellant Rocket Motors." It was accomplished under the technical direction of Mr. John Snyder of the Manufacturing Technology Division, Air Force Materials Laboratory (MATF), Wright-Patterson Air Force Base, Ohio.

Mr. S. P. Gualillo of Thiokol's Development Section was the Principal Investigator and Mr. W. I. Dale, Jr. of the Project Management Directorate was the Program Manager. Full authority for the management control of this program was the responsibility of Mr. G. F. Mangum of the Project Management Directorate. Others who cooperated in the work and in the preparation of this report are Messrs. E. H. Liggin, A. E. Graves, R. E. Askins, R. L. Murphy, Jr., C. S. Combs, J. M. Nelson, and Mrs. E. J. Grice of Thiokol, and Mr. William Abel of Illinois Institute of Technology Research Institute, Chicago, Illinois.

All pages, with the exception of Tables XL, XLI, and XLV, are unclassified. Only those Government organizations marked with an asterisk (*) on the distribution list will receive a copy of the report marked "CONFIDENTIAL" (Thiokol internal number C-68-10A). All other organizations will receive an unclassified copy having Tables XL, XLI, and XLV removed (Thiokol internal number U-68-10B).

This project was accomplished as a part of the Air Force Manufacturing Methods Program, the primary objective of which is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in economical production of Air Force materials components.

Suggestions concerning additional manufacturing methods development required on this or other subjects will be appreciated.

This report has been reviewed and is approved.

JACK R. MARSH, Chief
Advanced Fabrication Techniques Branch
Manufacturing Technology Division
Air Force Materials Laboratory

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GLOSSARY

AP	Ammonium Perchlorate
BF_3-400	Boron trifluoride (curing agent)
"B" Stage	An intermediate or partial cure of a resin system
Epon-828	Epoxy resin (Liquid)
Epon-1001	Epoxy resin (Solid)
ERC 2774	Epoxy resin (Liquid)
gpm	Gallons per minute
IITRI	Illinois Institute of Technology Research Institute
IITRI Combustible Core	Synonymous with Laminated Combustible Core
K_n	Ratio of burning surface area to throat area
MEK	Methyl Ethyl Ketone
Prepreg	Material such as cotton, or glass, in the form of a cloth or filaments which has been impregnated with a resin system and allowed to partially cure.
rpm	Revolutions per minute
Slip	Thin (watery) slurry
VYHD	Polyvinyl Chloride - Polyvinyl Acetate Copolymer
DOA	Dioctyl Adipate
LP-3	Polysulfide polymer
GMF	Quinone dioxime
DPG	Diphenyl guanidine
HX-874	Tri-functional imine
MgO	Magnesium Oxide
ZL-437	Polyester
Curing Agent Z	Modified polyamine
DOA	Dioctyl adipate
EPON 871	Epoxy resin (Shell Chemical Co.)
FcH	Ferrocene

SECTION I

PROGRAM INTRODUCTION

Rigid monolithic cores (mandrels) have long been employed to form the internal cavities in case bonded solid propellant rocket motors. The process is comprised of (1) accurately positioning the rigid core in the motor case, (2) casting the propellant around the core, (3) curing the propellant, and (4) removing the core from the motor. This processing technique is very adequate for relatively small solid propellant rocket motor manufacture.

The advent of the very large solid propellant Space Booster motors, up to 260 inches in diameter and approximately 900 inches long, has caused the method of forming the internal grain configuration to take on added significance. This has become a major manufacturing problem because of the unprecedented size of these motors. Rigid monolithic cores are not feasible because the great weight and bulk of such cores would make handling extremely difficult. Also, even slight adhesion to such a large area would necessitate tremendous forces for core removal. The very large Space Booster motors require that more serious consideration be given to the hydrostatic head of propellant, the greater magnitude of propellant slump, the large amount of heat to be removed from the cured propellant and the many problems associated with the design, fabrication and installation of such large cores.

Several approaches have been used in an attempt to overcome these problems. These include (1) hollow, segmented metal cores, and (2) retractable, segmented metal cores. The latter will be referred to in this report as a "collapsible core." Each of the above two techniques overcome some of the problems, but many still remain. There was, therefore, a need for developing the technology required to manufacture a core that would satisfy the special considerations associated with the very large motors. The purpose of this program was to help meet this need.

This report covers all of the work performed under Air Force Contract AF33(615)-2998, "Development of a Manufacturing Process and Associated Equipment to Improve Internal Core Forming in Solid Propellant Rocket Motors," and Modifications S/A 1, 2, and 3. This work was awarded in response to Thiokol Chemical Corporation Proposals HP-39-65, dated March 1965, and HP-39A-65, dated April 1965. The period of performance for the basic contract was 15 July 1965 through 15 October 1966. Modification S/A 1 to the basic contract authorized disposition of tooling after expiration of the period of performance.

Phase I effort was completed during the period 15 July 1965 to 15 October 1966. No work was performed from 15 October 1966 to July 1967 pending redirection from the Air Force. It was decided during this period to investigate further the castable combustible core concept with special emphasis on the WS-120A system. The scope of work was revised and formally presented in Modification S/A 2 of the contract. This revised scope constituted Phases II and III of the contract, and extended the period of performance from 15 October 1966 through 1 February 1968. Modification S/A 3 further extended the period of performance to 1 June 1968.

SECTION II

SUMMARY

This report covers all of the work performed under Contract AF33(615)-2998, and Modifications S/A 1, 2, and 3 for the development of a manufacturing process and associated equipment to improve internal core forming in very large solid propellant rocket motors. The program was divided into three phases:

Phase I - Evaluation and Selection of Design and Materials

Phase II - Castable Combustible Core Development

Phase III - TX11-37 Motor Demonstration

During Phase I five concepts for improved equipment for propellant cavity forming were evaluated. These were as discussed below.

Collapsible Core

The collapsible core is a segmented retractable steel core (which does not remain in the motor) that was designed, fabricated and successfully used in manufacturing the 156-inch space booster at the Space Booster Division, Thiokol Chemical Corporation, Brunswick, Georgia. This concept was rated second out of the five concepts evaluated under the current program. Costs were accumulated from Thiokol records. No effort, other than the evaluation, was expended for this concept under this program.

Membrane Core

A total of 7 membranes and 10 filler fluid materials were investigated. The membrane materials, which are thin plastic films, were placed in contact with various filler fluids to test for degradation in physical properties resulting from aging for 3 weeks at 145°F. Required concentrations and filler fluid-density relationships were established by tests. The successful membrane and filler fluid candidates were further tested for compatibility with propellant. Membrane materials were subjected to creep, peel, distortion and ignitability tests. The hazards of the various filler fluids were investigated. They were also tested for corrosion of various metals.

Mylar and CELANAR were selected as the membrane materials and zinc chloride, zinc bromide and clay slurries were selected as the filler fluids.

A design and tooling concept was developed and a tentative processing method was defined.

A number of problems became apparent. Although all appear to be capable of solution, feasibility was not proven in Phase I.

A cost and use evaluation of the membrane core concept was made and it ranked fourth in the evaluation.

Frangible Core

Of the concepts which were evaluated, the frangible core has the highest degree of proven feasibility (excluding the collapsible core, which has already been successfully used in a space-booster-size rocket motor) since TX33 motors have been successfully fired. Core and tooling design concepts and a processing method were evolved. This concept ranked first in the evaluation.

Laminated Combustible Core

In accordance with the contract, particular emphasis was directed toward the evaluation of the concept of cores manufactured using rigid combustible materials. This work was based upon previously successful development of combustible cartridge cases, at Illinois Institute of Technology Research Institute (IITRI). Because of their experience in developing combustible cartridge cases, a subcontract was awarded to IITRI for the development of a material to be used in rigid combustible cores. Laminated materials (fabric, resin and oxidizer) were selected for this work because they appeared to offer more freedom for tailoring physical and ballistic properties than the other materials with which IITRI had worked.

A number of formulations consisting of a resin binder, cotton gauze and ammonium perchlorate were made and then tested and evaluated by both IITRI and Thiokol. A final formulation, which would meet the structural requirements, was selected and fabricated into cylindrical cores. A total of 16 motors were test fired (core only) to study ignition and obtain ballistic properties of the material. Ignition requirements were learned but no ballistic property values were computed from these tests because of the erratic behavior of the material. Five motors were loaded using a combustible core and TP-H8163 propellant (Thiokol propellant formulated with PBAN polymer, epoxy cure agent, aluminum powder, ammonium perchlorate, DOA plasticizer and iron oxide). Separation occurred between the core material and the propellant due to the low extensibility of the material. After inhibiting the grains around the separations, they were successfully fired. Porosity, hygroscopicity, nonhomogeneity, erratic ballistic characteristics, low extensibility, and the processing of this material into large scale cores appear as major problems.

A design and tooling concept were made and a processing method was evolved.

A cost and use evaluation was made and this concept ranked fifth.

Castable Combustible Core

A limited amount of test and evaluation was undertaken to assess a structural propellant, developed under a previous Thiokol-sponsored program, for use as a combustible core. Seven motor firings were conducted to establish ballistic properties. Specimens were fabricated and tensile property data were obtained. Results indicated that with some additional tailoring to obtain the required physical properties, the material had excellent potential for this application. Additionally, this material had a number of advantages over the laminated combustible core. A design and tooling concept and a processing method were evolved. A cost and use evaluation was made and this concept ranked third. The collapsible core ranked second. However, since that concept is fully developed, the castable combustible core actually ranked second.

Evaluation of Concepts

As discussed above for each individual concept, a cost and use evaluation was made based on the results obtained during their investigation. Their order of rating is summarized below:

Frangible Core	1 (Highest)
Collapsible Core	2
Castable Combustible Core	3
Membrane Core	4
Laminated Combustible Core	5 (Lowest)

Phase I Conclusions and Recommendations

The following conclusions and recommendations resulted from effort expended under the Phase I studies:

1. The frangible and castable combustible core concepts were recommended for continued development. The selection of the program to be pursued depended on the desires of the Air Force.

2. The collapsible core is fully developed and the concept has been reduced to practice in the Thiokol 156-inch Space Booster motors.

3. The membrane core concept has many problems which could not be resolved in the Phase I effort.

4. Of the concepts investigated other than the collapsible core, the frangible core has the highest degree of proven feasibility.

5. The greatest effort in Phase I was expended on the laminated combustible core. The erratic behavior of this material and the complexity of fabricating a large space booster core are problems that would have to be resolved before it could be utilized as a practical core forming technique.

6. The limited amount of work performed on the castable combustible core indicated that it had excellent potential as an advanced technique for core forming in solid propellant rocket motors.

At the conclusion of the Phase I studies, the Air Force redirected effort on the program toward development of the castable combustible core concept, with special emphasis to be placed on the WS-120A system.

Phase II - Castable Combustible Core Development

During Phase II, an engineering analysis was performed for the application of the castable combustible core concept to the WS-120A system within the constraints imposed by the Thiokol TU-594 motor design. The analysis showed that the concept was not feasible for use with this motor because the modulus requirements, which evolve from the design constraints, are not compatible. A core thin enough to meet the ballistic

requirements and stiff enough to resist the hydrostatic head of the uncured propellant would have a modulus high enough to crack the propellant during cooldown and operation at 60°F. Ways in which the restraints could be changed to make the castable combustible core compatible with the WS-120A system are:

1. The web fraction of the motor could be decreased;
2. Internal support could be provided to the core during handling and prior to propellant cure;
3. The length of the motor could be decreased.

These changes are not recommended for the WS-120A system because they would decrease the efficiency of the motor without providing offsetting advantages for that particular system.

An analysis was also made of the core stability and bond stresses at the interface of the combustible core and propellant for a five-inch-diameter demonstration motor. On the basis of this analysis, requirements were established for the motor.

Core material tailoring was initiated concurrent with the engineering analysis. Thirty-six mixes of varying formulations were made and tested in order to establish the ranges of some of the pertinent properties. These data were screened and two formulations were selected for scale-up to a larger mix size for further characterization. The formulation having the greatest extensibility became the final choice for use in the demonstration motor. Additionally, processing techniques were established for mixing and casting the core material.

Phase III - TX11-37 Motor Demonstration

Based on the requirements which evolved from the analyses in Phase II, a five-inch demonstration motor was designed under Phase III. Core tooling was also designed and fabricated. Castable combustible cores were fabricated and used in casting four demonstration motors. The motors were static tested and the results were evaluated. The cores performed in much the same manner as other common propellants. The cores ignited the propellant in every test; however, there was an appreciable delay between core burning and propellant ignition. The most promising method for elimination of this delay appears to be reduction of the polymer-rich layer on the surface of the core.

The small motor demonstration phase of this program has shown that the castable combustible cores can best be used in motors of moderate length and/or web fraction. These cores may be most effectively used in motors that employ a core shape of such complexity that core removal is difficult and with grain configurations that are not already limited by propellant mechanical strain. In motors where propellant slump (in storage) may present a potential problem, the combustible core may afford an effective solution if the motor design is within the necessary constraints of web fraction and/or motor length. The feasibility of using combustible cores must be evaluated for each specific motor design for which they are considered.

It is recommended that a study program be conducted to resolve the core-propellant interface problem prior to use of the castable combustible core concept for a specific motor design. Any future work on this concept should consider temperature cycling of motors prior to static testing.

The castable combustible core materials that were studied are representative of a broad family of rigid combustible materials. By simple variations in ingredients these materials can be tailored to have wide ranges of physical and ballistic properties. Consequently, they should be considered for use in any application where rigid combustible materials are required.

The castable, combustible core material that was developed has a burning rate coefficient of pressure that is nearly zero. Consequently, materials of this type should be considered for any application in which minimum pressure sensitivity of burning rate is of prime importance.

SECTION III

OBJECTIVE

The original objective of this program was to investigate and evaluate techniques for forming the internal cavities in large solid propellant rocket motors. These techniques were (1) the membrane core, (2) the frangible core, and (3) the combustible core. This effort was to be directed towards improvement in the following areas: reduced costs, improved ability of the core to withstand hydrostatic pressure of the propellant, reduced cure time, increased shelf life, reduced handling hazards, and elimination of core removal operation.

The specific objective of Phase I was to evaluate the candidate processing techniques and make recommendations for the technique which should be further developed in subsequent phases, with particular emphasis being placed on investigation of rigid combustible materials, particularly those which had shown promise during the development of combustible cartridge cases. Near the end of Phase I, the most promising techniques were recommended for further investigation during Phases II and III. Work on these phases was not to begin until authorization was received from the Air Force.

At the conclusion of Phase I, the Air Force redirected effort on the program toward development of the castable combustible core concept, with special emphasis on the WS-120A system. However, it was determined by ballistic and structural analysis that the combustible core concept would not be feasible for use with the TU-594 motor designed for the WS-120A system. Therefore, it was decided to prove the concept in small demonstration motors rather than extend the analytical work without actual demonstration of the concept in motors.

Effort under Phase II was directed toward establishing proof of principal for the selected process by engineering analysis and by tailoring and characterizing the most promising core material formulation to be used in the feasibility tests of Phase III. The objective of Phase III was to verify by loading, casting, and static testing five-inch-diameter motors using the materials developed in Phases I and II.

SECTION IV

DESCRIPTION OF CONCEPTS

A. COLLAPSIBLE CORE

Although not included as one of the concepts to be investigated, this concept was included in the final evaluation because it had been fabricated and successfully used in the 156-inch diameter space booster motor. Actual costs were readily available and therefore established a base of reference. In essence, this is a retractable steel segmented core. The segments are ten feet high and consist of starpoint valleys and starpoint faces, all of which are capable of being remotely retracted after propellant cure. Figure 1 shows an overall view of the core which was actually used.

B. MEMBRANE CORE

The membrane core is a means of forming the internal grain configuration by using a thin flexible membrane that is shaped to the desired configuration by attaching it to templates at each end of the motor. Maintaining the position of the membrane and therefore the configuration is accomplished by filling the cavity inside of the membrane with a fluid whose density equals that of the propellant. A hydrostatic balance can thus be achieved. A "follower" is used to aid in configuration control in the vicinity of the propellant and filler fluid levels. After the propellant has cured, the positioning hardware is removed and the membrane material is either stripped away from the propellant or burned through on motor ignition depending on which method is the most feasible for the film used. A sectional schematic of this concept may be seen on Figure 2.

C. FRANGIBLE CORE

This concept consists of pre-casting segments of the core shape with polyurethane foam, inserting the core segments into the motor assembly, bonding them into an integral core and casting propellant around this foamed core. The core then remains in place until firing time when the foam is fragmented by an explosives network and expelled through the nozzle.

D. LAMINATED COMBUSTIBLE CORE

This concept consists of pre-forming segments of the core section of a combustible formulation that may be reinforced if necessary with cotton gauze or other compatible materials. The segments are then assembled and bonded together in tiers until the full core height is reached. The resultant shell, which will have the proper core configuration, is used as the mandrel and the propellant is cast around it. The core remains in the motor until it is fired. Ignition is accomplished in the normal way except that the core ignites first and it in turn ignites the propellant to which it is bonded. In essence, the core material becomes a secondary, structural propellant.

E. CASTABLE COMBUSTIBLE CORE

The castable combustible core concept is the same as the laminated combustible core in that they both contain rigid binders and inorganic oxidizers. The primary difference lies in the fact that the castable core is cast to the desired shape as opposed to the laminated core which must be wrapped on a mandrel and then machined to the required outside dimensions. Additionally, the required tensile properties are achieved solely through the use of a selected polymer rather than the use of cotton gauze reinforcement. This system produces a homogeneous material having predictable ballistics much akin to other common propellants.

SECTION V

PHASE I - EVALUATION AND SELECTION OF DESIGN AND MATERIALS

ACCOMPLISHMENTS

The objective of Phase I was to evaluate the candidate processing techniques and make recommendations for the technique which should be further developed in subsequent phases.

A. MEMBRANE CORE

1. Background

Thiokol's Sapce Booster Division in Brunswick, Georgia, began work on the membrane core concept several years ago. Considerable knowledge and experience were gained during an Independent Research and Development program[1].

2. Requirements

The requirements for the membrane core are given below:

a. The core must be able to withstand a compressive load of 64 psia at the forward end of the motor (as a result of the static head of the material) for 24 hours at 145°F.

b. The membrane must be an effective mold release if ignition cannot be accomplished through the membrane.

c. The membrane must be compatible with the filler fluid and with TP-H8163 propellant for up to 3 months storage.

d. The membrane should be selected so that ignition of the motor can be accomplished through the membrane, if possible. The ignition delay shall be less than 500 milliseconds and shall be reproducible within ± 15 milliseconds.

e. The membrane should have a tensile strength of not less than 4000 psi with uniform elongation properties along both the length and width of the sheet material.

f. The membrane should have minimum or no creep for a period of 20 to 30 days under operational tensile loading at 145°F.

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1. "Large Motor Core Technology Study," Independent Research and Development Program No. E-64-107/632, Thiokol Chemical Corporation, Space Booster Division, Brunswick, Georgia.

g. The membrane should have an elongation under tensile load of 4.0 pounds per linear inch, per mil of thickness, of less than 2 to 3 percent. This allows an increase in length under tensile load of approximately 2 to 3 feet (5 percent is about the maximum limit).

h. Low coefficient of friction in contact with the "follower."

i. The filler fluid must not create a hazardous condition if it is spilled on the propellant.

j. The filler fluid must be capable of being controlled at a specific gravity of 1.70 g/cc and heavier.

k. The filler fluid must be safe and easy to handle.

l. The filler fluid system must be equipped to provide a fluid at 145°F for casting and curing and at 60°F for cool down.

3. Materials Testing

a. Membrane Materials

An initial screening was made of the various commercial films that were commercially available and would generally meet the requirements of the membrane core concept. A list of properties of a number of commercially available films is given in Table I. Properties of several other classes of films are given in Table II. Costs of typical membrane materials are given in Table III. Based on this preliminary screening, the following materials were selected for further study:

Mylar "A"
Rhino 55
ACLAR 22 C
CELANAR 2000
CAPRAN 77C
VELOSTAT
H-Film

The material, type, thickness tested and supplier may be found in Table IV.

(1) Tensile Properties

All of the above organic films were found to be anisotropic. The machine direction is generally stronger than the transverse direction. A possible exception to this is CAPRAN 77C (See Table I). Any final design utilizing this concept would, therefore, have to consider the fact that the materials are not truly isotropic. For this evaluation, the tensile properties were determined in the machine or strongest direction and tested in accordance with ASTM D 882-61T. The tensile strengths of all of the above film materials met the requirements when tested at 77°F in an "as received" condition. These values will be found under the heading "Membrane Material Physicals Prior to Compatibility Tests" in Table V. Their suitability for this application,

however, was based on their residual strength after exposure to operational conditions. The degradation in strength is evaluated in the following section.

(2) Compatibility

(a) Membrane and Filler Fluid

The membrane materials mentioned above were tested for compatibility with each of the filler fluid materials that survived the solution preparation phase of this work. The fluids and membrane materials were placed in closed jars and conditioned at 145°F for three weeks. At the end of this period, those materials that survived were cleaned, dried and tested for tensile properties in the same manner as the untreated samples had been tested. The values shown in Table V are averages of 5 samples tested at 145°F. For ease of comparison, the first three columns in this table list the physical property values which were obtained for the membrane material at 77°F prior to compatibility testing. The "after test" values represent the total degradation of tensile properties and include the effect of exposure to operational temperature, filler fluid and elevated temperature testing. The tensile properties of all membranes degraded during compatibilty testing with the exception of zinc bromide and Mylar. This value for ultimate stress is improved by approximately 20 percent. Since this is beyond the range of experimental error, there appears to be a remote possibility that the zinc bromide actually improves the strength properties of Mylar.

The behavior of these thin plastic films after exposure to these various chemicals and elevated temperatures is significant. For example, after ACLAR was exposed to tetrabromoethane and tested, it exhibited a strain of 16 percent at a stress level of 1,889 psi. It then yielded to about half of this stress level and continued until it reached about 200 percent strain, then dropped in stress level again to about 400 percent strain. It then climbed to the same intermediate stress level until it reached 500 percent strain and then proceeded in a normal manner to reach a maximum stress which was about equivalent to the stress level at which it originally yielded. One of the specimens reached the machine limit at 600 percent strain. While at this constant strain, it relaxed to about 3/4 of the peak stress value and then broke. Other combinations exhibited yield points, some reached maximum stress at 50 percent strain and then dropped off to break at a considerably lower stress value. This erratic behavior suggests the following: (1) A more comprehensive study of thin plastic film behavior is desirable. (2) Creep may become a problem. (3) We should restrict ourselves to low strain values for design purposes.

(b) Membrane and Propellant

Five tensile specimens of each of four films were placed in contact (one side only) with uncured TP-H8163 propellant. The propellant was allowed to cure for 162 hours at 145°F. Three specimens of each of the four films were then subjected to tensile tests. The remaining two specimens were left in contact with the propellant and allowed to age for a total of 22 days. The reason for this additional exposure was to compare the appearance of the propellant surface for the two different exposure times. In both cases a thin coating of propellant adhered to the membrane material. In the case of the 162 hours of exposure, the appearance of the propellant and thickness of film left on the membrane were about the same as that reported in the peel tests.

After 22 days of exposure, the layer of adhered propellant was even thinner than in the case of the shorter exposure. In either case, there was no detrimental effect on the propellant surface. Althought this thin adhered film is referred to as propellant, it very likely consists primarily of polymer and plasticizer which tend to migrate to the outer surface of the grain.

For ease of comparison, the results of both groups of tests, as well as the original values of unexposed membrane (in parentheses), are presented in Table VI. In both cases the ultimate stress of the membrane is degraded after exposure to propellant. It may be seen that the yield stress of CELANAR and Mylar (polyesters) has shifted so that the stress at 5 percent strain is actually greater after 22 days than it was for the shorter exposure time. It is believed, however, that too much quantitative significance should not be placed on the results because of the small sample size used in these tests.

(3) Membrane Permeability

The membrane permeability test set-up, shown on Figures 3 and 4, consists of two half-pint mason jars. The two screw-top lids were soldered together and all but the moulded rubber seal was cut away leaving an exposed membrane area of 3.14 square inches. A hole was drilled in the top jar, which contained the filler fluid, and a rubber balloon was placed over this end of the jar to allow for expansion in the chamber. The bottom jar was filled with desiccant. Ren paste (an epoxy adhesive) had to be used in conjunction with the rubber gasket in order to obtain an effective seal. The results of these tests may be seen in Table VII.

Although the polyester type films (Mylar and CELANAR) showed the lowest permeability rate, all of the organic films and aqueous filler fluid combinations tested are premeable to some degree.

(4) Membrane Burst and Tear Strength

As may be seen in Table V, CELANAR, Mylar and H-Film all exhibit acceptable initial (Graves) and propagated (Elmendorf) tear strengths as well as Mullens burst strengths.

(5) Membrane Peel Tests

Test specimens of Mylar, H-Film, CELANAR and ACLAR were assembled, using TP-H8163 propellant, in accordance with standard Thiokol procedures which are used for propellant-to-liner peel tests. The results may be seen in Table VIII. Since the two films, Mylar and CELANAR, which were selected as most promising, are both polyesters, H-Film and ACLAR were also tested in order to note the degree of propellant adherence to two different chemical compounds; namely, polyimides and fluorohalocarbons. All films, with the exception of ACLAR (a fluorohalocarbon), adhered to the propellant. Should this concept proceed beyond Phase I and should subsequent firing tests prove that propellant ignition cannot effectively be accomplished through a Mylar or CELANAR film, ACLAR can be resorted to and stripped off prior to firing.

(6) Creep Tests

During the course of conducting tensile tests on the membrane materials, there was some evidence of creep (or more correctly plastic flow) in some of these organic films. Since this is a very critical property in assuming the performance of thin plastic films as membrane cores, it was deemed advisable to subject these membranes to tests for creep. The test set-up is shown on Figure 5. The design load (4 lbs. per linear inch per mil) was initially applied and all the specimens under test broke prematurely. The load was reduced to 25 percent of the design load and the test was repeated. The following films were tested: CAPRAN, Mylar, H-Film, CELANAR, Rhino 55, ACLAR and VELOSTAT. The test was conducted at 145°F. CAPRAN, Mylar, H-Film and CELANAR did not exhibit any creep after 18 days. Rhino 55 elongated 31 percent and then broke after one hour. ACLAR elongated 4 percent and then broke after one hour. VELOSTAT elongated and broke after 88 hours. The materials which have been tentatively selected, Mylar and CELANAR, do not exhibit any creep under these loading conditions. It is important to note that these materials did exhibit creep in other tensile tests performed under this contract. It therefore becomes a matter of defining the critical loading conditions under which creep will be manifested. This would entail an iterative process, working between the design load and 25 percent of the design load. It would also require that a comprehensive test program be performed under the environment that the membrane would see in actual application; namely, contact with propellant and filler fluid at a temperature of 145°F. Work of this extent was beyond the scope of this program as it was redirected.

(7) Distortion Tests

Specimens of ACLAR, Mylar, CAPRAN and H-Film were prepared for this test. VELOSTAT and Rhino 55 were eliminated because each is fabricated as a laminate with reinforcement threads placed between two layers of the plastic film. It was noted, during the course of conducting the tensile tests, that excessive distortion resulted from differences in elongation of base and reinforcement material. The specimens were prepared with longitudinal and horizontal lap joints so as to intentionally introduce "reinforcement" with seams that would simulate the seams that would result during the course of fabricating a membrane core. The residual effects of stressing are partially shown on Figure 6. Although these tests did not truly simulate the conditions which would be experienced in a large completed core, several significant facts became apparent.

a. Mylar, CAPRAN and H-Film tended to form ribs running parallel to the longitudinal joints. (This effect may be seen in the broken specimen of CAPRAN.)

b. In the case of the horizontal joints, "necking" occurred on one or, in some cases, both sides of the joints.

c. Local irregular spots appeared (as evidenced by the light spots) on the portions of the specimen that did not exhibit ribs or "necking" in the case of ACLAR, H-Film and Mylar. This effect indicates that these film materials are nonhomogeneous.

Although these distortion tests were not quantitative, they do indicate definite trends and behavior when in a strained condition.

(8) Flammability Tests

All of the candidate films were tested in a Bunsen burner flame (approximate flame temperature 1500°F). These tests were conducted to provide a preliminary visual evaluation of the film's burning characteristics. Even though these tests were not identical to motor ignition conditions, they serve as a guide in determining whether the membrane can be left in place after casting. Results of this work are described below:

a. VELOSTAT: This material, which consists of two polyethylene sheets between which are molded nylon reinforcing fibers, melts readily but burns slowly when compared to the other films. The reinforcing fibers melt and rapidly contract to form a ball that decomposes.

b. Mylar: Mylar contracts rapidly, forming molten balls that burn.

c. ACLAR: This film must be exposed to the flame for a slightly longer time than the other films before melting is initiated. Melting and decomposition take place as long as the material is exposed to the flame; however, it does not support combustion. Decomposition stops when it is removed from the flame.

d. CELANAR: CELANAR does not ignite readily. This material burns but is not self-sustaining.

e. Rhino 55: This material does not ignite readily. Melting and decomposition take place; however, it does support combustion.

f. H-Film: H-Film does not support combustion until the molten material has reached its decomposition temperature. At this point it will support combustion.

It is reasonable to assume that ignition through any of these films should not present a problem under actual motor firings in thicknesses of 8 to 10 mils. Additionally, prior experience at Thiokol's Huntsville Division has shown that ignition can be successfully accomplished through a viscoelastic barrier of 17 mils thickness.

(9) Adhesives and Sealing of Membrane Materials

Adhesives that were tested as possible sealants for film materials are shown on Table IX. These tests were conducted to provide a qualitative screening of candidate adhesives. Although Boxer Epoxy has excellent bonding qualities, it is quite rigid. Quantitative tests would be conducted prior to final adhesive selections.

ACLAR and CAPRAN were the only films that were successfully heat sealed.

b. Filler Fluids

A literature survey was conducted to select filler fluid materials that would satisfy the density requirements. The bibliography in this report included the sources of information used in making this survey. Three general classes of filler fluids; heavy organic liquids, aqueous solutions of inorganic salts, and suspensions, were investigated. A listing of the organic and inorganic materials and their densities may be found in Tables X and XI.

(1) Hazards

Most of the organic materials which meet the density requirement are either bromides or iodides, which are toxic. Hazards data on these organic liquids may be seen in Table XII. Hazards data on the solvents in which these organic materials are soluble, or miscible, may be found in Table XIII. Many of the inorganic salts, like the organic materials, are hazardous. These hazards may be found in Table XIV.

(2) Preparation Methods

(a) Organic Liquids

Three heavy organic liquids were selected for further investigation based on the data collected during the literature survey. These are: acetylene tetrabromide (1, 1, 2, 2 Tetrabromoethane), dibromobenzene, and ethylene dibromide. These organic liquids insured a complete selection of classes of materials, even though certain properties were undesirable. Ethyl alcohol was selected as the solvent for use in regulating the density. Dibromobenzene was eliminated as a result of these evaluations because of difficulties encountered in getting it tc form a solution. No trouble was encountered with the acetylene tetrabromide and ethylene dibromide and both satisfied the density requirement of 1.75 g/cc.

(b) Inorganic Salts

Ferric sulfate, zinc chloride, zinc bromide, stannous chloride, stannic chloride, and lithium iodide were selected as candidate inorganic salts. Cost had a great bearing on this selection.

Ferric sulfate was eliminated early in the evaluation because of difficulties experienced in getting it into a water solution. A yellowish percipitate formed in preparing an aqueous solution of stannous chloride; however, it was carried along in the evaluation since the precipitate could be filtered off or the liquid could be decanted. A great amount of heat was generated and hydrochloric acid fumes were liberated when stannic chloride was dissolved in water. No trouble was encountered in making an aqueous solution with the other inorganic salts. Air agitation, simple paddle mixers or recirculation effected adequate mixing. The required concentrations may be found in Table V.

(c) Suspensions

A limited investigation was conducted using ball clay slurries as filler fluids. The clays used in this work were EPD, Martin #5 and Jackson Ball Clay. All of these clays were air floated and water slurries were made in varying proportions in order tc obtain relative density values. The maximum density obtained in these tests was 1.634 g/cc. A 7/1 weight ratio of Martin #5 and Jackson Ball Clay was finally selected for deflocculation. A "slip" was made using 64 weight percent of this clay mixture with 36 weight percent of water. In each case, deflocculation was accomplished by adding 0.05 percent of sodium carbonate (based on weight of clay) and then adding 41° BAUMÉ sodium silicate. As optimum deflocculation is approached, the viscosity drops off rapidly so that a deflocculated slip would present no problem in pumping and recirculation. Although a deflocculated clay will usually stay in true suspension for several weeks, mild air or paddle agitation may have to be used to insure this. Based on this limited effort with clay slurries, we conclude the following:

1. The deflocculation process is extremely critical, but once accomplished, it can be duplicated.

2. Although we have not achieved a density greater than 1.634 g/cc, the clay supplier assures us that it is no problem to obtain ball clay-water slips having a density of 1.72 g/cc.

3. Preliminary work by the Kentucky-Tennessee Clay Co., Inc., indicates that a 70 weight percent mixture of ball clay and 30 weight percent of talc, feldspar, or flint will readily produce a density of 1.75 to 1.8 g/cc in about a 70/30 weight ratio of clay mixture and water.

4. The use of clay slips is feasible for this application if properly handled. The cost and safety advantages make clays attractive for consideration.

(3) Density - Temperature

Tests were conducted to obtain the density-temperature relationship for each of the filler fluid materials that were studied. These relationships may be graphically seen on Figure 7. The organic bromides have the greatest variation of density with temperature. This variation might constitute a control problem if temperature cannot be closely regulated during motor processing. On the other hand, this temperature dependence of density might be used as a means for obtaining the desired fluid density if it cannot be obtained through the use of concentration alone.

(4) Compatibility

(a) Filler Fluid and Propellant

Fifty-gram samples of uncured TP-H8163 propellant were placed in containers and covered with a 1/8 inch deep layer of the following filler fluids:

Zinc bromide ($ZnBr_2$) solution (Aqueous)
Zinc chloride ($ZnCl_2$) solution (Aqueous)
Clay/water slurry
Ethylene dibromide ($C_2H_4Br_2$) solution (Aqueous)

All specimens were placed in a steam table at 145°F. Samples were removed after 18 hours and visually inspected. The following results were noted with the various filler fluids.

a. Ethylene dibromide had been partly absorbed by the propellant. Cure had been inhibited, leaving the mixture in a liquid but somewhat viscous state.

b. Zinc chloride caused the propellant to have a lead-gray color on the upper surface and for some distance down into the propellant. Large surface cavities, probably due to gassing, were also noted.

c. Zinc bromide did not produce a noticeable color change; however, there was considerable evidence of voids and pockets caused by gassing.

d. The clay/water slurry had dehydrated leaving a dried cake of clay. The propellant had cured somewhat. It is believed that, in a closed system which would not allow the slurry to dehydrate, the water would affect the curing of the propellant.

It may be concluded from these tests that propellant cure would be inhibited in the presence of these aqueous solutions. Therefore, leaks from any source cannot be tolerated in any final application of this concept.

(b) Metals and Filler Fluid

4133 steel, 303 stainless steel, and 6061 aluminum were exposed to the three candidate filler fluids. The results shown in Table XV indicate that corrosion may become a problem and that corrosion inhibiting metals, such as stainless steel or other specialized materials, may have to be utilized if the filler fluid handling system is to be subjected to repeated use. Although this problem has several solutions, the increase in cost must be considered.

(c) Filler Fluids and Membrane Materials

This has been discussed under membrane compatibility.

4. Materials Evaluation and Selection

Material cost information and pertinent physical property values to assist in making a selection of compatible combinations of the most promising membrane and filler fluid materials are included in Table V. This evaluation was based on the following factors:

a. Physical survival of the membrane in the filler fluid.

b. Membrane tensile strength of at least 5000 psi at 5 percent strain (this is equivalent to the design requirement of 4000 psi plus 25 percent to allow for experimental error, etc.) after compatibility testing.

c. Permeability

d. Initial tear strength

e. Cost

f. Burst strength

g. Hazards

h. Availability in thickness of 7 to 10 mils

CAPRAN was eliminated because it dissolved in all the aqueous solutions and did not retain sufficient tensile strength at 5 percent strain.

VELOSTAT was eliminated with all filler fluids because of delamination problems and the extremely low tensile strength at 5 percent strain.

Rhino 55 was eliminated for the same reasons as VELOSTAT.

ACLAR was also eliminated because it did not meet the stress requirement at 5 percent strain.

H-Film was tentatively eliminated because, during the course of reviewing costs, it was found that thicknesses greater than 5 mils would not be available until early in 1967. Additionally, it is considerably more expensive than other suitable candidate materials.

CELANAR, likewise, is currently available in thicknesses up to 5 mils only. Its cost, however, is one of the lowest listed.

Mylar meets the general requirements which have been established for the membrane and will therefore receive first consideration in this feasibility study. A second choice would be CELANAR since thicknesses greater than 5 mils will be available late in 1966 and Phases II and III work could be carried out with 5 mil material.

The order of preference for the filler fluid to be used with the selected membranes is as follows:

1. Zinc Chloride
2. Zinc Bromide
3. Clay Slurry

Clay slurry was placed in third position because the technique of preparing slurries was not carried to completion. Additionally, a closed fluid handling system would have to be used.

5. Design Concept

The design concept for the membrane core is basically as described earlier in this report. The details of implementing this design into a practical method of forming an internal core are best described in a discussion of the tooling concept which follows.

6. Tooling Concept

Figures 8, 9, 10, 11, and 12 are concept sketches for tooling and equipment to be used with the proposed membrane core. A bill of materials may be found in Appendix A. This concept embraces the stretching of a thin membrane the total motor length which will conform to the conventional starpoint configuration. Propellant and a filler fluid are placed on opposite sides of the membrane to maintain a hydrostatic balance. The major components of this system are as follows:

Forward end hold-down device
Membrane
Follower
Tool Column
Aft end tie-down and tensioning device
Level control system
Fluid circulation and conditioning equipment

The design concept for the forward end hold-down device is depicted on Figure 8. The components of this device are an adapter, lock ring, center post, hold-down bar and the segmented structure which forms the mandrel configuration. The adapter serves as a jacking point and as the fluid inlet and outlet to the inside of the membrane. The center post bolts to the motor case and extends up into the motor forming a center support for the core segments. The segmented structure is made of keyed segments which form the mandrel contour and compress the membrane boot to provide a seal between the propellant and the fluid. The hold-down bar pulls down on the primary segments of the segmented structure effecting the seal mentioned above. The lock ring is the means by which this pressure is applied. The hold-down ring and the segmented structure contain matched slots such that the entire device may be disassembled and removed through the head-end opening of the motor.

The membrane stretches between the forward and aft holding devices and forms the motor cavity. A flexible boot of appreciable thickness will be bonded to the forward end of the membrane. The boot will be premolded to the desired head-end configuration of the mandrel. It will be compressed by the head-end hold-down device to form a seal between the propellant and the fluid.

The tool column extends the length of the motor case and is keyed in such a manner as to align the head-end and aft-end hold-down devices and the follower.

It will be constructed of tubing in 10 feet lengths to facilitate handling. The forward portion will fit inside the hold-down bar but will not be attached. The 10 feet lengths will be attached with shoulder bolts with the heads recessed. The aft length will have a position to mount a hydraulic jack for applying tension to the aft-end hold-down device and the membrane.

The follower travels inside the membrane and is keyed to the tool column so that it remains aligned with the aft-end and forward-end hold-down devices. It will be approximately 60 inches long and will be positioned so that approximately 12 inches extend above the propellant line. The float switch, proximity switch and the level rod will be mounted on the follower. To facilitate movement, it will contain ball bushings to roll on the tool column.

The aft-end tie-down device, as shown on Figure 9, serves three purposes. It acts as an anchor for the aft portion of the membrane; it contains means for tensioning the membrane; and it contains means to align the aft portion of the mandrel with the motor case. This device will be fabricated of light gage metal and will provide the grain configuration to the aft portion of the membrane. The membrane will fold over the top surface of the structure and will be clamped in place with a clamp strip. An alignment lug on each of the starpoints will align the aft portion of the mandrel with the casting sleeve. The device will slide on the aft tool column segment and will be attached to the hydraulic jack, which will rest on the tool column, by means of an adapter.

The level control system maintains prescribed levels between the filler fluid and the propellant. It consists primarily of matched lengths of bayonets, air line and cable to the followers, which are attached to the casting elevators. When the elevator reaches its maximum height a length is removed from each of these parts to maintain the proper elevations. The elevator travel is controlled by a system now available at Thiokol's Space Booster Division. This consists of a low-pressure probe which extends to near the end of the bayonet. When the propellant covers this probe a back pressure results that operates a pressure switch, which actuates the operating mechanism and raises the elevator. When the elevator rises, it will also raise the follower which will cause the float switch to be above the level of the fluid. The float switch will actuate a motorized control valve that will allow the fluid to fill the mandrel until the float switch reaches the proper level. A magnet, mounted on the air line probe, and a proximity switch on the follower will check alignment after linkages have been removed, and actuate a signal if improper alignment exists.

The fluid circulation and conditioning equipment is required to add filler fluid and to recirculate conditioned fluid within the core cavity. The flow diagram for this system, shown on Figure 10, will operate in the following manner. During the casting operation the fluid will be brought to the site in a tank truck which will have its own pump. The liquid will be pumped from the tank truck through the heat exchanger into a surge tank. The heating medium in the heat exchanger is steam, and a thermostatically controlled steam regulator valve controls the amount of steam and thereby controls the temperature of the heated fluid. The fluid in the surge tank may be recirculated through the heat exchanger to maintain the desired temperature. The surge tank will contain enough fluid for approximately 24 hours of casting time. When the follower inside the membrane rises, actuating the float switch, it opens a motorized control valve, which allows the filler fluid to flow into the head-end of the motor by gravity flow.

This flow will continue until the flow control valve, by means of the float switch, shuts off the flow. A schematic of electrical connections is shown on Figure 11.

The recirculating rate is approximately 800 gpm. This rate provides a rise rate of approximately 0.05 ft/sec within the membrane. During cure and cool down the fluid will be pumped from the bottom of the motor by a 2000 gpm pump, through the head exchanger and, by means of a flexible line, returned into the top of the motor. The cooling medium will be well water at 600 gpm and 68°F. No refrigeration equipment is provided for the cooling water and it will be dumped after use. The heat exchanger will be used to heat and cool the fluid as required. When heating, steam will be used in the exchanger and the water will be valved off; when cooling, the reverse will occur.

In the event it should be desired to ship the motor with the fluid retained within the cavity, closure concepts for the case and nozzle are presented on Figure 12. The case closure is a large plate which covers the aft case opening and bolts to the case flange. It contains a fill port which is blanked off and sealed after the cavity has been filled. The nozzle closure seals on the exit cone of the nozzle and allows the motor cavity to be filled to that point. The closure consists of an aluminum beam which may be inserted through the nozzle throat and floats on the fluid. It has rubber pads which bear on the nozzle entrance cone and a pivotal center post which, by means of a hold-down nut, pulls down the aft-closure plate and seals the motor. The aft-closure plate contains a fill port which may be blanked off and sealed when the motor is full of fluid.

The method of assembly, disassembly and use of this equipment is described below. The first step is to fabricate the membrane. The membrane must contain longitudinal and radial markings which will allow it to be installed on the holding devices in proper orientation and in such a manner as to provide uniform tension. The head-end boot may be attached at the motor loading site or manufactured as an integral portion of the membrane. To install the core in the motor case, the follower and aft-end hold-down are clamped together and the aft portion of the membrane is pulled over these two ports and secured to the aft surface of the aft hold-down. The assembly is then suspended from a crane over the motor and the membrane is lowered into the motor. The head-end hold-down assembly is installed and secured in place. The tool column is installed with sections added and bolted together as it is lowered through the aft-end hold-down device and the follower. After the tool column is seated in the head-end, the jack is placed on the aft-end and by means of an adapter is attached to the aft-end hold-down device and tension is applied to the membrane. The matched lengths for the bayonets, air line and follower cable are attached to the casting elevator and the follower is lowered to the head-end of the motor case. The casting and filling operation then proceeds until the motor is filled. After the grain is cured and finished the aft portion of the membrane is released from the aft hold-down device and is pulled across the aft portion of the grain and secured and sealed with a potting compound. The follower, aft hold-down device and tool column are removed from the motor. The desired closure is then placed on the motor and the cavity filled and prepared for shipment. At the launch site the fluid is drained, the aft closure removed, the head-end hold-down device dismantled and removed through the head-end case opening and the membrane stripped from the motor. The motor is then ready to be fired.

7. Processing Method

The process which was proposed for the membrane core concept may be described step-wise as follows:

a. Assemble head-end fixtures to case.
b. Attach membrane to aft hold-down fixture.
c. Lower into position and attach membrane to outside of case at aft end.
d. Install tool column.
e. Assemble and install head-end hold-down assembly.
f. Install follower.
g. Install aft hold-down fixture.
h. Attach membrane to aft hold-down assembly.
i. Install bayonets and level control.
j. Install aft-end jack and adapter.
k. Tighten membrane.
l. Lower follower into position for start of casting.
m. Hook up fluid system.
n. Cast.
o. Monitor system during casting.
p. Remove aft hold-down fixture.
q. Remove follower.
r. Remove tool column.
s. Bond membrane to propellant.
t. Install aft closure.
u. Fill with fluid.
v. Monitor during shipment.
w. Pump out fluid.
x. Dispose of fluid.
y. Remove aft closure.
z. Remove forward hold-down assembly.
a. Remove boot and membrane.
b. Remove forward boss fixture.
c. Return reuseable items and fluid to loading site.

8. Core Problem Areas

a. Creep under tensile load during motor casting and cure operations.
b. Hourglassing or longitudinal ribbing resulting from possible non-uniformity of membrane tensile properties, circumferential and longitudinal seams.
c. Possible relaxation of the membrane above the core forming follower caused by friction load which propellant static head imposes on the membrane and follower.
d. Problems associated with inspecting assembled membrane for leaks at panel seams, pin holes and other possible incipient or undetected flaws.
e. Restoration of core shape if fluid level of filler fluid rises above the propellant level in the motor. Filler fluid must lag propellant level because of non-uniformity of propellant level around core during casting operation. However, this increases friction load between follower and membrane.

f. Fluid circulation during cure may cause distortion of configuration.
g. Maintaining of proper core geometry of the casting surface and intimacy of contact with the core forming follower.
h. Monitoring what is taking place beneath the level of propellant and filler fluid.
i. Corrosion of the fluid handling system.
j. Leaking of filler fluid into the propellant.

B. FRANGIBLE CORE

1. Background

Considerable work has been done by Thiokol on the frangible core technique. A program[1] conducted by Thiokol in 1964 demonstrated the feasibility of this concept in motors containing up to 7,000 pounds of propellant. The core was fabricated using a polyurethane foam (Thiokol Rigithane 334 with T-327 cure agent), with "Pyrocore" detonating cord embedded in its outer surface. The polyurethane was selected after a literature survey of previous work had been conducted. The density of the foam in the large motor was approximately 6 pounds per cubic foot. Very little change in ignition characteristics was experienced when these 7,000-pound motors were fired with the core in place. Motor ignition was accomplished by means of a dual system consisting of a PYROGEN igniter and the "Pyrocore." A use and cost evaluation was conducted. The system design was based on extrapolations from previously available information, none of the extrapolated values were confirmed in the laboratory and no materials were tailored for this particular application.

2. Requirements

a. The core must be able to withstand a compressive load of 64 psi at the forward end of the motor as a result of the static head of uncured propellant for 24 hours at 145°F.
b. The core must be compatible with an effective mold release.
c. The core must be compatible with TP-H8163 propellant for up to 3 months storage.
d. Core fragmentation must be thorough enough to permit expulsion of the core pieces through the nozzle without increasing the chamber pressure above 1100 psi.
e. Use of the frangible core shall not result in ignition delays in excess of 500 milliseconds. The delay should be reproducible within ± 15 milliseconds.

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1. "A Feasibility and Test Program for Demonstration of Integral Mandrels for Large Solid Propellant Motors," Contract NAS 1-3516.

3. Design Concept

a. Core

The design is based upon foaming the individual starpoints in sections 10 feet long. This is accomplished in a mold using a polyurethane foam (Thiokol Rigithane 334 with T-327 curing agent).

The individual starpoints are then assembled and properly aligned around a positioning drum and bonded to each other with adhesive. Tiers of starpoints, thus assembled, are built up until the 85 foot long core is completed. The interfaces between the tiers are also bonded.

Sufficient data for tensile, shear and compressive strength of Rigithane 334 foam were available from previous work. Analysis of the strength requirements for a frangible core to be used in manufacturing a motor 156 inches in diameter and 85 feet long indicated that volumetric compressive deformation was of primary concern. The bulk modulus requirement was based on allowing 1 to 1-1/2 percent volumetric compression of the foam under the hydrostatic head imposed during loading of the motor. Past experience in manufacturing a 156-inch motor indicated the hydrostatic head was approximately 65 percent of the calculated value or 42 psi. In this case, the bulk modulus required for 1 percent compression is 4200 psi.

None of the physical property tests for Rigithane 334 foam were performed at 145°F, the temperature to which the frangible core will be subjected during propellant casting. Data were available for foam of various densities tested at 77° and 120°F and an extrapolation was used to predict the foam density required to satisfy the calculated strength requirements. It was estimated that a density of 16 pounds per cubic foot would be required in the head end of the motor where the hydrostatic head is greatest. Measurements of foam strength as a function of foam density were not made because they were not included in the scope of this contract.

Since the hydrostatic force decreases along the length of the core from the bottom to the top of the motor, the density of the foam may be decreased proportionally. The density distribution initially selected for evaluation is 16 lb/ft^3 for a 20-foot length of the forward section of the core, 12 lb/ft^3 for the next 20 feet, 10 lb/ft^3 for 20 feet, and 8 lb/ft^3 for the last 25 feet of the aft section. These densities may be higher than will actually be required but are considered suitable for determining costs of manufacturing a frangible core. An analysis was performed of the tensile and shear requirements and of the compressive strength required to resist the bearing load applied to counteract the buoyancy force. The foam densities selected to satisfy the volumetric compression requirements possess more than sufficient strength for these other properties, assuming the data obtained by extrapolating to 145°F are correct. The tensile strength for Rigithane 334 foam with a density of 8 lb/ft^3 is adequate for withstanding loads during handling and assembly of the frangible core in the motor case.

New foam materials recently marketed may be worthy of consideration, but some development would be required to determine whether they meet the requirements for use as a frangible core.

b. Fragmentation System Design

A feasible system for fragmenting the foamed core has been designed and is depicted on Figure 13. Selection of this system was based on the frangible core dimensions and densities discussed in the preceeding sections. Using data available on the explosive load of pyrotechnics required and the extent of fragmentation observed in firing TX11, TX19 and TX33 motors containing frangible cores, an extrapolation was made to determine the material and spacing required for fragmentation of the higher-density foam to be used for the 156-inch frangible core. The system will consist of detonating fuse installed near the longitudinal centerline of each starpoint in an amount proportional to the foam density (Figure 13). The installation of the fuse will be performed after the propellant has been cast. The fuse would then be detonated by phase sequencing through the use of "delay devices" as follows:

Time	Event Initiated						
		Starpoint					
(milliseconds)	Pyrogen	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
0	X	X					
5			X				
10				X			
15					X		
20						X	
25							X

The core design which is proposed herein for the 156-inch space booster motor requires an explosives system which has a higher energy output than the system which Thiokol has successfully used in the TX33 frangible core tests. This is dictated by the increased foam density and web thickness.

Pyrocore, which comprised the basic explosives system for the TX33 motor, is not available in explosive loading densities greater than 20 grains per foot. This relatively low explosive loading density would then result in an excessive number of strands per unit volume of foam, which would have to be distributed on the surface, and in multiple perforations in the starpoints. The decision was therefore made to use "Primacord" with an explosive loading density of 60 grains per foot. The use of Primacord as detonating fuse offers the following advantages:

a. Primacord is available with a plastic sheathing, while Pyrocore has a lead sheathing, resulting in a ligher, easier to handle sub-assembly; i.e. easier to bend, join, and feed into the perforations.
b. The raw materials and labor involved in fabricating the explosives network will be lower in the case of the Primacord.
c. Off-the-shelf time delays and connectors are available for Primacord.
d. Strands may be "bundled" around a central strand very readily by taping.
e. The individual strands which comprise the "bundle" will always sympathetically detonate the adjacent strand, thus ensuring complete propagation. Pyrocore may not sympathetically detonate the adjacent strand.
f. No additional hazard is involved since Primacord and Pyrocore have the same explosives hazard classification.

4. Tooling Concept

Sketches of the frangible core, starpoint mold, core support drum, and assembled starpoints are shown on Figures 14 through 17, respectively.

The starpoint mold will be coated internally with a release agent which will also act as a sealant for the wood mold. The mold will also be provided with a one-inch cylindrical mandrel (also coated with a release agent), which will be positioned in the center of the starpoint cross section, to form a longitudinal hole for the insertion of one element of the fragmentation network.

The positioning drum is fabricated in 10-foot-long sections and coated with a release agent on its exterior. The sections are then assembled around an existing tool column with an O-ring between each section. The drum sections will be keyed into the tool column for alignment and the starpoints will be aligned from indexing marks on the drum. The use of a positioning drum also reduces the amount of foam required to less than one-half the total core volume of the 156-inch motor.

5. Processing Method

The process which was proposed for this concept is relatively simple and may be described step-wise as follows:

a. A two-component foaming machine will be used in order to produce a foam of uniform and reproducible density.
b. The foam will be cast into 10-foot-long starpoint molds and cured.
c. After removal from the mold, spurs will be trimmed.
d. The starpoints will be inspected for dimensional and density compliance.
e. Any voids will be repaired at this point.
f. A compatible adhesive will be troweled on to the starpoint mating surfaces.
g. The assembled starpoints will be held in place with web strapping until the adhesive has set.
h. Excess adhesive will be removed prior to adhesive cure.
i. This process will be repeated with subsequent tires of starpoints until the desired height is reached. Adhesive will also be applied in the girth joints between tiers. The last tier will have to be cut to the proper length.
j. The web strapping will be removed and the entire core will be inspected.
k. MR22 mold release agent will next be sprayed over the entire core surface.
l. The prepared motor will then be cast with propellant and allowed to cure.
m. The core support drum will then be disassembled and removed in 10-foot sections.

6. Problem Areas

Although no major problems are anticipated, there are several factors that will require experimental confirmation in any continuation of this concept. Among these are:

a. Verification of the physical properties for Rigithane 334 foam at 145°F in the density range of 6 to 16 lb/ft^2.

b. Effectiveness of Primacord in fragmenting the foam.
c. Possible inhibition of propellant surface due to impingement of foam.
d. Adequacy of predicted delay periods in fragmenting the starpoints.
e. Problems normally associated with the scale-up process.

C. LAMINATED COMBUSTIBLE CORE

1. Background

Considerable effort has been expended through the years by a number of companies on the development of a combustible core. Much of this effort has been concentrated on foam materials which incorporated an oxidizer. Other work has utilized felted nitrocellulose or similar materials. The results of effort using the foam materials with an oxidizer have been poor. Uncontrollable and unpredictable porosity has caused excessive burning rates and resultant overpressurization of the motor cases during firing. Work with the felted materials has been confined to very small motors.

The Illinois Institute of Technology Research Institute (IITRI), formerly Armour Research Institute, has had a great deal of experience in the development and manufacture of consumable cartridge cases. Their efforts have covered felted nitrocellulose and similar materials, as well as resin-oxidizer-fabric laminates. It was decided to have IITRI work with Thiokol, under a subcontract, to develop the combustible core material.

Discussions with IITRI personnel were held to determine the best approach to be taken. Because the scope of this program was such that only one technique could be considered, it was decided that effort should be confined to the resin-oxidizer-fabric reinforced laminates. It was the consensus that the degree of freedom in tailoring the formulation to meet the desired properties was much greater than with the other materials with which they had worked.

It was also determined that, even though IITRI had considerable experience with these materials in their consumable cartridge case programs, they did not have data on tensile properties or burning rates. These data had never been required by the users of the consumable cartridge cases.

2. Requirements

a. Basic

The original basic requirements for the combustible core material, which were prepared by Thiokol and transmitted to IITRI at program inception, are listed below:

a. The core must be capable of being ignited at chamber pressures less than 750 psi.
b. The core must be able to withstand a compressive load at the forward end of the motor of 64 psi, as a result of a static head of uncured propellant, for 24 hours at 145°F.

c. The core must be compatible with an effective mold release.
d. The core must be compatible with TP-H8163 propellant for up to 3 months storage.
e. The core must burn rapidly enough for it to be consumed in less than 500 milliseconds without creating chamber pressures in excess of 1100 psia. This delay should be reproducible within ± 15 milliseconds.

The formulation of the first samples sent to Thiokol basically attempted to duplicate the formulation most recently developed under a previous contract. These samples were meant to serve as a starting point in the development of the combustible core material. After assessing the physical property values of these samples, it was decided to reexamine the physical property requirements which would permit bonding the core to the propellant as opposed to having the core "free floating." After considering the problems inherent in the two methods, it was decided to bond the propellant to the core in order to eliminate the possibility of cracking and uncontrolled burning that might result in the failure of the entire motor. This decision therefore eliminated the need for item c, above, of the basic requirements and changed the physical property requirements for the core material. IITRI was advised of these changes.

b. Ballistic

It was recognized that the material to be utilized should be compatible with the 156-inch diameter space booster, and it was decided that the following conditions should exist in establishing the ballistic requirements for the combustible core:

a. The maximum rate of mass discharge of the core should not be greater than the maximum rate of mass discharge for the motor itself. This condition permits the motor to use the combustible core without decreasing the safety factor of the case.
b. The thrust produced by burning of the core should be less than the weight of the motor. This provision assures that the motor will not lift off the pad during core burning and later return to the ground if the propellant fails to ignite. It was determined that this condition would be met if the product of characteristic velocity (C*), burning rate (r_b) and density (ρ) is less than or equal to , 49.93. The calculations used in determining that $C^* \, r_b \, \rho \leq 49.93$ may be found in Appendix B. Expressing requirements for ballistic characteristics in this way permitted IITRI maximum freedom in material selection.

c. Structural

An investigation was conducted to study the core material properties and their compatibility with the stresses and strains induced in both the propellant and core material as part of the study conducted prior to making the decision to bond the propellant to the combustible core. The combustible core material is used to form the internal cavity of the 156-inch space booster in this application, and is burned away when ignited. The core material must remain bonded to the propellant when the motor is subjected to low temperature storage [(+60°F) for space booster applications] and pressurization. If separation between the core and propellant occurs, it is possible

that the burning surface would increase threefold, which would result in overpressurization of the motor. Consequently, this investigation was directed towards determining the allowable core material properties which would not impose excessive stresses and strains on the propellant grain when the temperature of the motor is lowered to the storage temperature of + 60°F.

The following core material properties and core thickness were arrived at in this investigation:

Modulus of Elasticity	200, 000 - 250, 000 psi
Extensibility	4. 0 percent minimum
Tensile Strength	5, 000 psi minimum
Coefficient of Thermal Expansion	0. 8 - 5. 0 x 10^{-5} in/in-°F
Core Thickness	2 inches

The results and method of analysis are shown in Appendix C. It can be noted that the requirements shown above are not identical to the results obtained in the analysis. This variance is the result of practical design considerations.

3. Material Development

All combustible materials which were formulated by IITRI consisted of three basic components - oxidizer, fabric and resin. The oxidizer in all cases was ground ammonium perchlorate while the fabric used for reinforcement was cotton gauze (similar to surgical gauze). Two resin systems were used:

Thermoplastic - polyvinyl chloride - polyvinyl acetate (VYHD)
Thermosetting - epoxy resins

Other resin systems investigated, but rejected for various reasons, are listed in Table XVI.

The first samples made by IITRI were based on VYHD, the resin system with which they had obtained most success during the previous development of combustible cartridge cases. The purpose of making these samples was to assure that the process that had been used previously could be reproduced reliably. In this way these samples provide a connecting link between the early work and the development work which was to be performed. Test of VYHD samples indicated that materials of this type would be too soft at high temperature for the required use; consequently, further consideration of this system was abandoned.

Two cure systems were investigated for Epon-1001 resin; namely, hexahydrophthalic anhydride and BF_3-400. Hexahydrophthalic anhydride was eliminated because it caused charring of the gauze. The Epon-1001 was later modified with Epon-828 to reduce prepreg brittleness. During the latter part of the program, IITRI investigated a resin system consisting of Epoxide ERL-2774 and HB Polymer. Based on physical property data supplied to Thiokol at a meeting with IITRI, it appeared that ERL-2774 and HB Polymer (approximately 50/50) offered the greatest promise of meeting the physical property requirements. Effort was then concentrated on optimizing this resin system. The effect of HB Polymer content on the physical properties of the resin system can be seen on Figure 18.

Preparation of the evaluation samples was as follows: Prepregs were first prepared by coating a solvent, oxidizer and resin slurry onto cotton gauze. (The gauze was a surgical grade, 36 x 44 mesh, 7" wide and 50" long.) The guaze was placed on a Mylar covered glass plate and coated with the slurry by means of a scalpel. A 0.005-inch clearance was provided between the scalpel and the glass. The coated gauze was then air dried for 16 hours. The air dried gauze was then vacuum dried at 40°C and 0.1 mm Hg absolute for another 16 hours, after which it was stored at 5°C until used for lamination.

The prepreg was then trimmed into 6 x 6 inch sheets and laminated between two heated platens in a hydraulic press to a thickness of 1/8-inch.

Processing variables, such as laminating pressure and temperature, will be discussed under physical properties.

IITRI assigned a sample number to each specific formulation. Samples of formulations sent to Thiokol are listed, with their identification number, in Table XVII. Formulations reported by IITRI, but not supplied to Thiokol, are listed in Table XVIII. The sample number referenced to may be used in lieu of the formulation in later discussions in this report.

4. Process Development

The process used in making evaluation samples did not lend itself to the fabrication of large cylindrical cores. It became necessary, therefore, to design and fabricate equipment for coating, rewinding, and convolute wrapping.

a. Coating Equipment

The fabric slit coater utilized is shown on Figure 19. For the purpose of this program, the coater was mounted in a horizontal position, which allowed direct mounting of a funnel-shape slurry reservoir directly above the metering block. The metering block had an 18 x 1-inch feed slot directly below the slurry reservoir. The lower surface of the metering block was ground and polished to match the ground and polished backup plate. The backup plate could be accurately positioned at a predetermined distance from and parallel to the metering block. The distance between the plate and the block provided the slit width, which in turn controlled the amount of slurry deposited on the carrier material as it passed between the block and the plate.

The carrier material was pulled from the stock roll (Figure 19), over a positioning roll, and through the slit of the coating equipment. The coating equipment was designed to coat only the central 18 inches of the carrier material. The slit, however, could pass carrier material as wide as 25 inches. This design provided dry outboard edges to permit handling or alignment corrections while the equipment was in operation.

b. Rewind Equipment

The rewind strand for the coated gauze, shown on Figure 20, consisted of two 3-inch diameter aluminum rolls and a drive mechanism mounted on an aluminum angle frame. The rewind strand controlled the rate of movement of the carrier material through the coating box and provided a takeup roll for the dry coated material.

The drive mechanism imparted roll surface speeds from 4 to 18 in/min. The lower, or drive, roll was positively driven by sprockets and a roller chain from the output shaft of a 36:1 speed reducer. Power was supplied to the speed reducer through a set of Varicone pulleys and from a 30 rpm gear-head electric motor.

The drive roll, the peripheral speed of which was positively controlled, pulled the carrier material through the coating box by means of the friction between the coated gauze and the aluminum roll. The upper, or takeup, roll was driven by a friction-clutch drive from the lower roll. This drive allowed the takeup roll to rewind the coated gauze at a changing rate to compensate for increase in roll diameter.

c. Convolute - Lamination Equipment

The convolute-lamination equipment, shown on Figure 21, was composed of a driven mandrel, a heated-platen pressure roll, and a pregreg supply roll. The mandrel was an accurately machined and polished roll driven by a 30 rpm gear motor through a Varicone variable-speed drive and sprocket-chain system. This system permitted the use of mandrel speeds from 2 to 12 rpm. The mandrel was mounted in split bearings to allow quick interchange with other mandrels and thus permit on-the-mandrel curing of the core. The mandrel diameter used for fabrication of the cores was 2.750 + 0.002 inches.

The mandrel was backed by a floating-platen roll mounted in a set of guideways. The guideways provided parallel alignment of the platen roll with the mandrel roll. The platen roll was free floating in the vertical direction. Air cylinders, attached to the end bearings of the platen roll, applied a controlled load to the platen. A controlled orifice leak in the pneumatic pressure line between the pressure reducer and the air cylinders allowed back-off of the platen as the core diameter increased.

The hollow platen was heated by a circulating heated fluid passing through it. The fluid supply lines were connected to the platen roll through rotating seals and a flexible metal hose. The heat-transfer fluid (Therminal FR-2) was heated externally in a temperature-controlled bath, pumped through the platen roll, and returned to the bath.

d. Processing of Cylindrical Cores

(1) 7/8-Inch Wall Core Cure

The B stage cure was accomplished by heating the core on the mandrel to 80°C for 16 hours. This time included the warmup period of the core and the mandrel.

The temperature of the oven was then increased to 135 ± 3°C and held at that temperature for 48 hours. The core and the mandrel were then cooled to ambient temperature, the core was removed, and the samples were machined to size. Figure 22 shows a typical core prior to removal from the mandrel. The first core was cut into 3-inch lengths in accordance with Thiokol's request. These 7/8-inch wall cores were used for ignition tests by Thiokol.

(2) 1/8-Inch Wall Core Cure

The thin 1/8-inch wall cores permitted a decrease in the time required for both the B stage and the final cures. B stage cure was obtained in 16 hours at 80°C, and final cure required only 24 hours at 135°C.

5. Materials Test and Evaluation

The tests which follow will be discussed for both the development formulations and the final formulation which was selected.

a. Structural Properties

Tensile strength, modulus of elasticity and elongation will be discussed together since they may all be computed from the same test data and are interdependent. Tensile strength was measured in accordance with ASTM D 638-64T.

Tensile properties are sensitive to ammonium perchlorate, resin content and processing parameters. This can be noted in Tables XIX through XXIV. The data in these tables show that as the laminating pressure is increased, the tensile strength and modulus of elasticity also increase. The effect on elongation is not as pronounced, but it generally tends to decrease. An increase in ammonium perchlorate content (and decrease in resin content) produces a decrease in tensile strength.

Table XIX shows that elongation is improved if HB polymer is incorporated with epoxy resin. The final formulation selected was based on these data. Tensile data obtained for flat samples of the core material delivered to Thiokol are shown in Table XXV. An examination of the 40-hour cure time data (which most closely approximates the cure time of the delivered cores) shows that the tensile properties at 145°F do not fulfuill the requirements mentioned earlier in this report. The samples were too weak and were not extensible enough; they may be barely stiff enough.

b. Density and Porosity

Density is an important parameter since it affects the ballistic product stated in the requirements and also burning rate. The effects of laminating temperature, laminating pressure and ammonium perchlorate content on density may be seen in Tables XXIV and XXVI. The porosity of the delivered core formulation is a direct function of density as shown in Table XXVII. It varies from approximately 10 to 22 percent. The theoretical density for this same formulation is 1.612 g/cc or 0.0582 lbs/in^3.

c. Thermal Coefficient of Expansion

These tests were conducted on a sample (IITRI Number 16747-21-6) which was made up as a flat laminate of the same composition as the cores delivered for static tests. The coefficient of thermal expansion was determined both parallel and normal to the laminates. The following results were obtained:

Normal to Laminates:

-90°F to +30°F: 6.36×10^{-5} in/in-°F

+30°F to +90°F : 5.51×10^{-5} in/in-°F

Parallel to Laminates:

+90°F to -10°F : 3.49×10^{-5} in/in-°F

-10°F to +120°F : 2.14×10^{-5} in/in-F

Since circumferential growth is of primary concern in this particular application, the coefficient of thermal expansion parallel to the laminates has greater significance. This value is well within the requirements ($0.8 - 5.0 \times 10^{-5}$ in/in-°F) set forth by Thiokol for the temperature range of +60°F to 140°F. The value obtained normal to the laminates is only slightly higher than the requirements.

d. Gassing and Swelling

These tests were conducted with specimens cut from IITRI sample number 16747-21-5, which was one of the cylindrical cores from which sections were cut for static tests. One sample was cut longitudinally out of the cylinder wall, while another was cut across the radius (90° to the cylinder axis). The length, width and height of each sample were measured with a micrometer and the weight of each sample was also obtained. The samples were then subjected to a vacuum of 29 inches of Hg for seven days at 140°F. These measurements were repeated with the following results.

Longitudinal sample did not indicate any weight or dimensional change. The sample cut across the radius did not show any dimensional change but did show a small loss in weight (.53 percent). It can be concluded from these results that gassing and swelling should be no problem at the propellant cure temperature.

The samples used in the above test were then subjected to a density check with the following results.

The longitudinal sample had a density of 1.3960 g/cc while the sample cut across the radius had a density of 1.3315 g/cc. These densities are generally representative of density values obtained from samples cut from the same core section. The difference in the two values is not believed to be a result of orientation of the fabric within the samples. These density values agree well with the value of 1.345 g/cc for this core material prior to testing. This stability of density therefore confirms the conclusion that gassing and swelling should be no problem during motor processing.

e. Compatibility and Adhesion Tests

A specimen approximately 2 x 2.5 x 7 cm, weighing 37 g, was prepared from IITRI's sample number 16747-13-5. A 3/8-inch layer of TP-H8163 propellant was cast on top of the 2.5 x 7 cm face, so that the interface was normal to the direction of the laminations. It was felt that this would represent the worst conditions if migration of propellant constituents were to take place. The prepared specimen was then cured

for six days at 140°F. Hardness was checked parallel to the laminations prior to casting propellant on the sample. It was believed that this would give some indication of core material binder degradation adjacent to the propellant. After the 6-day cure period, a good bond appeared to exist between the propellant and the core material. The propellant was then cut away from the specimen, leaving only a layer a few mils thick on the specimen. A 1/8-inch slice was then cut off one end for microscopic examination of the interface. Color photographs at 70X magnification showed no evidence of any appreciable migration. A surface discoloration, only, was noted. The thin layer of propellant on the remainder of the sample had to be scraped off in order to check hardness again. Resulting data are:

Period	Hardness (Shore "D") (Average of 10 readings)
Before	56
After	54

An excellent bond appeared to exist although quantitative values were not obtained. This should not be misconstrued as being indicative of the behavior of the bond during propellant cure shrinkage. This will be further assessed in actual motors loaded with core material and propellant. It is our opinion that the indicated change in hardness is not significant enough to indicate any serious degradation.

f. Differential Thermal Analysis

The maximum cure temperature used for the preparation of study samples was 135°C. Differential thermal analysis (DTA) of the combustible core material provided information useful in optimizing cure temperature with respect to minimum curing time, yet made no compromise with safety.

The instrument used was the Fisher Model 260 differential thermalizer. This model consists of three separate units: a furnace, a solid-state programmer, and a sample holder. A Microcord 44 recorder (Photovolt Corporation) completes the instrumentation system.

The procedure for thermal analysis is outlined in Fisher catalogue No. 10-560V1 and was used for all samples tested. Sample weights were maintained at 25 mg but were diluted with 75 mg of alumina. This method of sample preparation minimized the amount of sample present in the crucible, yet maintained a mass approximately equal to that of the reference crucible. The quantities of sample and reference material should be approximately the same in each crucible to minimize baseline drift in the thermogram.

The first thermograms (Figure 23) were of the individual components of the combustible core material. The heating rate was 10°C/min, and the temperature limit was 500°C. The recorder chart speed was 10 in/hr. This chart speed resulted in the thermograms with easily discernable sharp peaks.

The thermograms showed that the components exhibited no radical temperature transients below 200°C. The epoxy resin (Epon 1001/Epon 828/2 percent BF_3-400)

was only mildly exothermic throughout the heating range, and the thermograms indicated that curing was complete at ~ 400°C when the heating rate was 10°C/min.

Differential thermal analysis of cured combustible core material showed that the first deviation of the thermogram, which occurred between 175 and 200°C, was only slightly exothermic. The most recognizable feature in all of the thermograms was the endotherm associated with a phase change in ammonium perchlorate at 243°C. This temperature varied only 2°C for all samples that contained ammonium perchlorate. Decomposition was evidenced by strong exothermic reactions at temperatures higher than 243°C.

The thermograms obtained from the three basic systems studied are presented on Figure 24. The characteristic ammonium perchlorate endotherm at 243°C was again evidenced. Data from these thermograms, given in Table XXVIII, showed that the thermograms for combustible core material were characterized by the thermally induced changes associated with ammonium perchlorate.

The heating rate was changed from 10°C/min to 5°C/min in a second series of DTA studies. The samples were granulated combustible core material that contained 13.41 percent gauze, 63.81 percent ammonium perchlorate, and 22.78 percent resin. The resin was 70 percent Epon-1001 and 30 percent HB polymer. The thermograms showed that the lower heating rate did not change the characteristic endothermic and exothermic temperatures (Table XXVIII). The lower heating rate did provide greater detail for the thermograms, but the differential temperature was lower and the peaks were broader.

The Fisher differential thermalizer allows the operator to stop the heating-rate program at any time; the programmer can maintain the furnace temperature at this point for any indefinite period. With this feature in mind, a series of DTA runs was made in which the furnace temperature was allowed to rise in 50°C increments at the 10°C/min heating rate and was held after each incremental step for 60 minutes from 0 to 400°C. The data showed that sustained elevated temperatures did not affect the thermally induced transients of combustible core material. These data indicated that the combustible core material is chemically stable at the 135°C process temperatures and no deleterious effects, due to temperature, were noted below 200°C under various conditions of DTA.

g. Autoignition Temperature

This test produced information important to the safe processing, handling and storage of rocket motors containing combustible cores. It also gave an indication of the threshold temperature required for ignition. The core material used in this test was sample number 16283-18-10 and consisted of the following:

Ammonium perchlorate	60.7 weight percent
Gauze	11.8 weight percent
Resin	27.5 weight percent
Epoxide 2774 / HB polymer	1:1 ratio

The data obtained from this test are shown in Table XXIX. The "all fire" and "no fire" temperatures for this material are higher than most Thiokol propellants; therefore, it can be concluded that this material is sufficiently safe in this respect.

h. Ignitability

This test was conducted on material from the same sample that was used for the autoignition tests and employed the hot filament technique. The purpose was to obtain information that would assist in sizing the pyrotechnic igniters for static tests. The resulting data were plotted, along with data for other propellants, in order to assess its relative ignitability. This plot (Figure 25) shows that the combustible core material is more difficult to ignite than such "common" propellants as TP-H8126 and TP-H8047. The data for two propellants (TP-H7031 and DTS-6130) that are more difficult to ignite than the combustible core material are included on this plot for comparative pruposes. These propellants are characterized as having large fuel and oxidizer particle additives to make them "cool-burning" and no burning rate catalysts.

It can be concluded then that the combustible core material would require more ignition energy then "common" propellants to initiate burning, but less energy than "special" or underoxidizer compositions.

i. Hazards Testing

Tests conducted by the Interstate Commerce Commission (ICC) classified the laminated combustible core as Class B explosive under ICC regulations. The results of the tests which formed the basis for this classification may be noted in Appendix D of this report.

j. Burning Rate - Pressure Relation

All of the initial testing of burning rates for material evaluation was conducted by burning strands parallel to the laminates. The fair-to-poor degree of correlation obtained between Thiokol and IITRI tests is shown in Table XXX and Figure 26. The burning rate of this laminated core material is sensitive to ammonium perchlorate content, laminating temperature and laminating pressure (density - porosity). This can be seen in Tables XXXI and XXXII and is shown graphically on Figures 27 and 28. The results of burning at lower pressures may be seen in Table XXXIII. It may generally be concluded from these data that; (1) as laminating pressure is increased, the burning rates tend to decrease; (2) as laminating temperature is increased, the resulting burning rates have higher burning rate exponents.

The above correlations which have been established are based on longitudinal burning. Burning in a rocket motor would actually take place in a transverse direction. The preparation of strand burner specimens for transverse burning was more difficult because of insufficient sample thickness. IITRI devised two methods for specimen preparation. These are shown on Figures 29 and 30. The longitudinal and transverse burning rates (using both methods) for a high and a low density material are shown in Table XXXIV. Results of limited tests indicate that transverse burning rates differ from longitudinal burning rates by factors varying from 10 to 40 in low density materials and by a factor of 1.4 in high density material. Since these tests were conducted at one pressure only, IITRI was unable to obtain a value for the burning rate exponent

when burning occurs in the longitudinal direction. In an attempt to obtain a value for the burning rate exponent, Thiokol used one-inch-long samples as the strand length from a material similar to the final delivered cores. One specimen was burned at 500 psi and two were burned at 700 psi. The results are shown on Figure 31. The burning rate exponent (η) in the equation $r = \beta P^{\eta}$ was 0.52

where

β = temperature constant

P = pressure (psi)

η = burning rate exponent

After noting the difference between longitudinal and transverse burning rates, it became evident that in an actual motor firing the burning rate would be a result of the combined burning rates. This conclusion was based on the results of laboratory tests conducted under ambient conditions in which samples were initiated to burn transversely; however, burning also propogated laterally through the gauze.

It was concluded from these burning rate tests that actual motor firings would be required to produce realistic ballistic data.

k. Closed Bomb

Closed bomb tests were conducted to determine the ballistic characteristics of two different oxidizer levels. The calculated energy values for combustible core materials with minimum and maximum ammonium perchlorate content may be found in Table XXXV. The calculations may be found in Appendix E.

l. Vented Bomb Tests

Vented bomb experiments were undertaken by IITRI to evaluate the burning rate characteristics of combustible core material under simulated motor operating conditions. The following core material formulation was used in these tests:

Ingredients	Weight, %
Ammonium Perchlorate	65.0
Gauze	12.0
Resin	23.0
Density (lbs/in^3)	0.051

The vented bomb in which this experimental work was conducted is shown on Figure 32. The throat area in this bomb is 0.0385 in^2, and the free volume is 4.58 in^3. The igniter consisted of 1.1 grams of M-9 mortar flake and an M-52 electric primer. All samples weighed 3.85 grams. All specimens were inhibited on five sides; and, in every case, burning was transverse to the laminations.

A shear disc was employed to give uniform starting pressure. The pressure at which the disc sheared appeared to be 200 to 300 psi. The specimen sizes which were tested are:

Web Thickness (in)	Surface Area (in^2)	K_n
0.125	1.310	34.6
0.250	0.657	17.3
0.500	0.330	8.69

Figure 33 shows the pressure-versus-time trace for the igniter only. Figures 34, 35 and 36 show the combined effects of igniter and combustible core material at various K_n values. It will be noted that equilibrium pressure was achieved only at a K_n value of 17.3 and lower. These low K_n values would be unacceptable in the design of a large motor such as the 156-inch space booster motor that operates at a K_n value of 135, which is more typical of the K_n values at which motors normally operate.

(1) Analysis of Results

The burning rate at the equilibrium pressure recorded on Figure 35 was determined from the following relationship:

$$P_{eq} C_d A_t = \rho A_s r$$

where:

P_{eq} = equilibrium pressure (1250 psi)

C_d = discharge coefficient (0.00738 sec^{-1})[1]

ρ = density (0.051 lb/in^3)

K_n = ratio of surface area to throat areas (17.1)

r = burning rate

Substituting the above values, the calculated burning rate at 1250 psi is 10.6 in/sec. This data may be further utilized to determine burning rate characteristics by evaluating equilibrium pressure as a function of the burning rate exponent (η) in the following equation:

$$P_{eq} = \left(\frac{K_n \rho}{C_d} \right)^{1/1-n}$$

1. This value was arrived at by using calculated values of thrust coefficient and specific impulse as reported in the monthly report of February 1966, and substituting these values in the equation $I_{sp} = \frac{C_f}{C_d}$

where:

$$\beta = \frac{r \text{ @ } 1250 \text{ psi}}{1250^n}$$

The plot shown on Figure 37 is the result of these calculations which were developed for the values of K_n (ratio of burning surface area to throat area) used in this series of vented bomb tests. The plot indicated that the range of burning rate exponents necessary for the equilibrium pressures which were experienced in the vented bomb tests, must be greater than 0.7 and less than 0.95. The resulting burning rate coefficient β would then be greater than 0.0212 and less than 0.0715. The degree of significance which can be attached to this plot is questionable since it was derived from one experimental pressure value and assumed values of "n" to solve for β.

6. Motor Firing Tests and Evaluation

The cylindrical core material delivered to Thiokol for motor firing tests are listed by sample number, wall thickness and composition in Table XXVII. All of the cores had inside diameters of 2-3/4 inches and were approximately 12 inches long. The first core was cut into 3-inch-long pieces (sample number 16747-12-I, II and III). The inside and outside diameters had been machined to hold tolerances. A visual examination of the ends of the cylindrical pieces showed evidence of porosity, resin-rich and resin-starved areas. The second core that was delivered (sample number 16747-13-5), although improved, still showed some evidence of nonhomogeneity. The nonhomogeneity of the two cores is illustrated by the X-ray view shown on Figures 38 through 41. All of the subsequent cores having a 7/8-inch wall thickness showed evidence of this nonhomogeneity (to a lesser degree) on visual examination. All machined samples were hygroscopic to some degree and had to be dried prior to use.

a. Exposure to Output of Pyrotechnic Igniter

A total of 18 TX11 motors were fired to evaluate the core material only (no propellant). Motors numbered 1, 2, 3 3A, 4A, 4B, 4C, 5 and 6 were fired in an attempt to optimize the igniter output in order to obtain good ignition of the core material. All motors were prepared by "potting" 3-inch-long sections of the core material into short-length TX11[1] motors as shown on Figure 42. All core surfaces, with the exception of the inner cylindrical surface, were inhibited. In preparation for these tests, two TX96-3 igniters (25 grams of TICI pellets) were tested in empty TX11 motors (Nos. 1 and 2) having the same nozzle throat diameters as planned for use with two live grains (Motors Nos. 3 and 4). The throat areas for these two motors were arrived at by using β, n, and C* values supplied by IITRI. Burning rate and density were assumed from previous IITRI data, and initial and final pressures were predicted using the relationship:

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1. A TX11 motor is a heavy walled test motor routinely used for batch testing of production lots of propellant. The motor case has an inside diameter of 5 inches and is available in 6 or 12 inch lengths. The forward and nozzle closures are sized to accommodate standard igniters and nozzle inserts. The overall length with a 12 inch long case is approximately 18 inches.

$$P^{(1-n)} = \frac{C^* \beta \rho A_s}{g A_t}$$

where:

n = burning rate exponent

P = pressure

C* = characteristic velocity

ρ = density

β = burning rate coefficient

A_s = burning surface

g = gravitational acceleration at earth's surface

A_t = throat area

Since the pressure had to be kept within the motor design limits, throat areas of 1.0 in^2 and 0.90 in^2 were selected for the first tests.

The igniter pressure-versus-time traces obtained, shown on Figures 43 and 44, could then be used to determine the igniter energy input needed for the motor ballistics evaluation.

The first test (Motor No. 3) was performed in a short-length TX11 having a 1.0 in^2 throat but no ignition occurred as evidenced by the comparison of Figure 45, which is the pressure-versus-time plot for this motor, with Figures 43 and 44 (Motors No. 1 and 2, respectively). The difference in maximum pressure is due to the free volume differences.

The original objective of the test was to evaluate the ballistic properties of the core material; however, since ignition did not occur, it was possible to examine the combustible core after exposure to the output of a TX96 igniter containing 25 grams of TICI pellets[1].

The surface of the combustible core exposed to the direct impingement of hot igniter gases was unaffected. There was no evidence of erosion from the flame jets which issued from the igniter nor was there any evidence that the combustible core material burned partially and went out. The material was, therefore, unchanged structurally. Although the normal surface of this material is very hard and glazed like a laminated plastic, it had not been anticipated that the material would withstand the effects of igniter output without some signs of erosion or burning.

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1. Boron-potassium pellets.

The igniter output was increased and the nozzle throat diameter decreased to 0.90 in^2 for a retest of Motor No. 3. It was believed that these changes would result in a longer igniter action time at a higher pressure within the motor. These changes were effected and the retest of Motor No. 3 was attempted. The motor ignited; however, it blew up shortly after ignition. A plot of this test is shown on Figure 46. It should be noted that the igniter action is also plotted on this figure for information. The chamber pressure was approximately three times the expected pressure. In this test, the initial K_n was 29 and the final K_n was 47.

Since Motor No. 3 did ignite and blew up from overpressure, it was then decided to test another motor with a larger throat. In the interim, a third igniter design, with still more output, was fabricated and pressure-versus-time tests were made in empty motors having the same free volume and nozzle sizes as Motors No. 3 (as tested) and 4 (to be tested). The igniter pressure-versus-time traces are shown on Figures 47, 48 and 49.

The testing of Motor No. 4 was then attempted with the same type of igniter that was used in Motor No. 3. The sound of this motor, as heard over the test pit intercom, indicated that only the igniter burned (See Figure 50). The third type of igniter was installed in the motor while it was still in the stand and again the sound was typical of igniter action only (See Figure 51). Since there were no audible indications that the motor had burned, testing was terminated for review and evaluation. Subsequently, examination of the motor and igniter, however, showed that the combustible core did burn long after igniter action on the first attempt (hang-fire) and consequently, there was no record because the oscillograph had been turned off. The second igniter that was installed and fired in this motor was, therefore, superfluous.

The erratic response of the combustible core material to igniter output and the vast spread in burning rate from motor blowup to inaudible burning makes it difficult to draw firm conclusions. It is evident, however, that the modified igniter used for the retest of Motor No. 3 and the initial test of Motor No. 4 provided sufficient energy for the combustible core material even though the ignition delay of Motor No. 4 cannot be readily explained. (This igniter is shown on Figure 64.) Since the combustible cores in these motors were supposedly identical, it appears that factors such as surface condition, moisture, nonhomogeneity, etc., affected ignitability, or this material exhibits an extreme sensitivity to pressure.

Table XXXVI presents a summary of all motors that were fired as a part of the ignition study.

b. Motor Firings to Obtain Ballistic Properties of Laminated Core Material

The testing up to this point had not produced any reproducible ballistic data on the core material. To this end, the testing of core material only was continued using the same motor configuration that was used in the ignition study. However, a much broader range of burning-surface-to-throat-area ratios were used in this series of tests, which are listed in Table XXXVII. Twelve motors were loaded with combustible core 7/8-inch segments. Motors numbered 1, 2, 3, 3A, 4A, 4B, 4C, 5 and 6 were discussed and summarized under Section V, C. 6. a in this report. Pressure-versus-time curves for test firings of Motors No. 7 through 14 may be seen on Figures 52 through 59. Motor No. 15 has not been tested because the igniter plug became jammed in the igniter port. A summary of motors fired with combustible cylindrical cores

(2-3/4 inch I. D., 4-1/2 inch O. D. x 3 inches long) may be found in Table XXXVII. The burning time reported is the time when the pressure first returned to zero. Periodic burning (chuffing) after the pressure first returned to zero was audibly and visually observed for several seconds with Motors No. 7, 8, 9, 11, 13 and 14. Chuffing times of 26.7 seconds and 35.9 seconds were measured for Motors No. 13 and 14, respectively. Chuffing times for other motors were not measured, but are estimated to be of the same order of magnitude. It can be noted under remarks in Table XXXVII that the clouds of black smoke subsided only after the initial K_n value was increased to 100.

All fired motors contained residue (carbonized gauze) to some degree. Figures 60 and 61 show the residue left in Motors No. 5 and 6, respectively, which represent the most extreme conditions. The residue decreases with increasing K_n.

The pressure-versus-time traces for Motors No. 7, 8 and 9 (Figures 52, 53 and 54) all show several oscillations as the pressure increases. These are attributed to instrumentation.

Motors No. 10 through 15 were set up so that two motors might be fired at each of three K_n values. These three pairs of motors were fired at increasingly higher K_n values than Motor No. 9. Referring again to Table XXXVII, it will be noted that, in each case one motor blew up, while another ignited and burned (with chuffing) at the same K_n.

An additional motor, No. 16, which is not shown in Table XXXVII, was also fired with igniter only. This test was conducted in order to check out the performance of the optimized igniter when using the smaller throat sizes required by the higher K_n values. A throat diameter of 0.523 inches was used (same as Motors No. 11 and 14), as against 1.184 inches used in Motor No. 4. It may be noted by comparing the pressure-versus-time traces shown on Figures 62 and 48 that a higher peak pressure was developed.

The following may be concluded from the test firings that have been conducted using the IITRI combustible core:

1. Motor firings to date have not produced any usable values for burning rate, characteristic velocity or other necessary ballistic properties.
2. The behavior of the combustible core in its current state of development is erratic and different from normal solid propellants.
3. The mode of burning is still not understood. That is, it is not known whether the core material is burning perpendicular to the laminates, parallel with them, or otherwise.
4. Motors with the same K_n operate differently. One motor will burst while another chuffs.
5. Chuffing occurs even at relatively high K_n values.
6. The mode of discharging solid residue out of the motor is not understood. It does not appear to be a gradual scarfing away of the surface. The residue may retain its structural integrity up to some point and may then be ejected in a mass great enough to offer nozzle restriction. All motors have had undesirable residue after firing.

7. During tests at Thiokol, stable combustion was not obtained at the low K_n value (17.3) for which stable burning was reported by IITRI. Stable burning was still not attained when the K_n was increased to as much as 140, a value closer to that used in large space booster motors.

c. Motor Firings Using Laminated Combustible Core and Propellant

Five of the cores delivered to Thiokol were fabricated specifically for use as cores in loading sub-scale TX11 motors. These cores had an inside diameter of 2-3/4-inches and a 1/8-inch wall thickness. Their composition, which is basically the same as for the cores having a 7/8-inch-thick wall, may be found in Table XXVII (samples 16747-21). Since the outside diameter of the core and the inside diameter of the insulated case fixed the web thickness of the grain at 0.9 inches, the grain length was calculated to be 7.639 inches based on a decision that the initial and final burning surfaces were to be as near equal to each other as possible. Using this core length, TP-H8163 propellant was cast into the motor. After curing for 6 days at 145°F, a visual examination revealed separation between the cores and the propellant grains. In each case, the separation was localized for a distance of 0.50 to 0.75 inch in width along the circumference of the interface. The actual separation was estimated to be 0.030 to 0.040 inch and ran the full length of two of the grains. X-rays taken at 0° and 90° confirmed this. Although we originally intended to inhibit only the ends of the core, of necessity, we had to also inhibit across the separation and overlap the inner edge of the grain end for a distance of 0.25 inch. A sketch of the final configuration may be seen in Figure 63. The igniter (Figure 64) which was successfully used in igniting the core material in the motors listed in Table XXXVII was also used in firing these motors. The motors were fired at various K_n values as shown below:

Motor No.	K_n	Throat Area (sq. in.)
1	100	.880
2	125	.707
3	150	.587
4	175	.503
5	150	.587

The propellant ignited and burned normally in each case. The pressure-versus-time traces for these motors are shown on Figures 65 through 69. Delayed ignition can be noted on Motor No. 1. Chuffing occurred for approximately 1.5 seconds before the propellant ignited. The propellant performed in a predictable manner; however, the core material continued to exhibit erratic behavior. This may be noted by comparing the pressure-versus-time traces for Motors No. 3 and 5, which were both fired at the same K_n (150).

7. Design Concept for Large Motors

The design concept, as envisioned for adapting a laminated combustible core to a large motor of Space Booster size, would consist of scaling up to the bench process developed by IITRI. Longitudinal sections, two inches thick, would be wrapped around mandrels of appropriate cross-sectional geometry to form elements of the final large core cross section. These various elements would then be machined and bonded

together to form a segment of the final core. Segments would then be stacked in tiers and bonded together until the final core length was developed.

8. Tooling Concept for Large Motors

Special as well as off-the-shelf-type tooling would be required to implement this concept. The anticipated prepregging process, which would be required to coat the cotton gauze with a resin and ammonium perchlorate slurry to a specified thickness, is shown on Figure 70. The prepreg would then be wrapped onto mandrels of 2 different cross-sectional geometries and cured (in explosion-proof ovens) as shown on Figure 71. After stripping these shapes from the mandrel, they would be cut longitudinally and the edges would be machined (in an explosion-proof mill) as shown on Figure 72.

9. Processing Method

It is desired to point out that the core fabrication process, which is generally described below, involves the fabrication and machining of a material which is essentially a propellant. Since the combustible core is in every sense a propellant, strict compliance with accepted safety standards would be mandatory:

a. The cotton gauze would be pre-impregnated with a mixture of ammonium perchlorate, HB polymer, Epon-1001, and solvent as shown on flow sheet, Figure 70. At this point, the prepreg may have to be "B" staged to permit handling and storage.
b. The coated gauze would then be wrapped on mandrels having two basic configurations; a triangular and oblong cross section as shown on Figure 71. The wrapping would continue until the desired thickness (2 inches) is obtained.
c. While still on the mandrel, the material would be "B" staged at 80°C for 16 hours and given a final cure at 135°C for 48 hours.
d. The core sections would be stripped from the mandrels in a specially designed stripping machine.
e. The triangular sections would then be longitudinally sawed into 3 equal angular pieces while the oblong section would be sawed into 2 channels or "U" sections as shown on Figure 72. The edges would then be milled to provide a tongue and grove, "lap" or "V" joint. These sections are envisioned as being no longer than 10 or 12 feet for ease of handling.
f. The prepared shapes would then be mated and bonded together using a combustible adhesive. Radial bonds must be provided between tiers. An alignment jig would also have to be provided for this assembly operation.

10. Problem Areas

a. Nonhomogeneity of the material which is inherent in the manufacturing method.
b. Erratic behavior on ignition and burning.

c. Density variations within the same fabricated piece.
d. Uncontrollable porosity which will be considerably aggravated in 2-inch thicknesses.
e. Ballistic parameters are still unknown.
f. Low extensibility.
g. Problems associated with scaling up from a 3-inch diameter cylindrical core to an intricate star-shaped configuration of considerably larger diameter and web thickness.
h. Complexity of large core manufacturing.
i. Limitations of the process in producing complex cross-sectional geometries and contouring of the forward ends of cores.

D. CASTABLE COMBUSTIBLE CORE

1. Background

A structural propellant was developed approximately 2 years ago in connection with Thiokol-sponsored work for a "case-on-propellant" study. It was also considered for a combustible rocket motor case, but it lacked the necessary physical properties for this application. The anisotropic characteristics and problems associated with porosity and burning rate variations of the laminated combustible material developed by IITRI prompted Thiokol to review the structural propellant for use as a combustible core. This structural propellant appeared to have none of the disadvantages and some advantages over the laminated combustible core. Additionally, the physical properties were of the same general order of magnitude as those required for the combustible core.

Mr. John O. Snyder, technical manager of this program for the Air Force Materials Laboratory, visited Thiokol for a program review. Samples of this structural propellant were shown to Mr. Snyder along with its physical and ballistic properties. It was mutually agreed that the material might be modified to meet the requirements of a castable core and that its feasibility should be investigated further. Mr. Snyder further approved the evaluation of the castable combustible core concept along with the other concepts being evaluated in this program.

2. Requirements

The requirements for the castable combustible core are similar to those listed for the laminated combustible core (Section V. 6. 2. a, b and c).

3. Test and Evaluation

The decision to evaluate the castable combustible core was made late in Phase I. As a result, only a limited amount of development was possible during Phase I. Most of this work was concentrated on ballistic properties.

a. Ballistic Properties

Considerable latitude is permissible in complying with the ballistic product (40. 9) cited in the requirements. Figure 73 shows the general area of interest within which the ballistic tailoring can be accomplished. It was felt that the most expedient method of obtaining ballistic properties would be to fire small single-perforated grains

(approximately 1/3 of a pound) in sub-scale TX405[1] motors. The first formulation consisted of:

55 percent AP (75 percent unground, 25 percent ground)

45 percent Epoxy resin (Z curing agent)

Four firings were made using this formulation at various K_n values as shown below:

Motor No.	Average Pressure (psi)	Burning Rate (in/sec)	K_n
1	120	.059	1798
2	290	.064	994
3	320	.064	736
4	480	.06	446

The pressure-versus-time traces for these firings may be seen on Figures 74 through 77. It will be noted that normal pressure-versus-time traces were obtained and that no ignition problems were encountered. The burning rates, however, were too low.

In view of the low burning rate obtained, three more grains were fabricated in which 1 percent of a burning rate catalyst was incorporated. These grains were test fired in TX11 motors. The results may be seen below:

Motor No.	Average Pressure (psi)	Burning Rate (in/sec)	K_n
1 (Mix 14)	100	.1	210
1 (Mix 15)	250	.156	251
2 (Mix 15)	400	.17	283

Pressure-versus-time traces for these test firings may be seen on Figures 78, 79 and 80. Using the characteristic velocities calculated from the firing test data of these motors and an average density of 0.06 lb/in^3, the ballistic products, shown below, are well within the requirements (49.9 maximum).

Motor No.	C^*, ρ, r_b
1 (Mix 14)	19.8
1 (Mix 15)	37.0
2 (Mix 15)	36.1

1. A TX405 is a small "work-horse" type test motor which is used to assess the ballistic properties of small laboratory lots of experimental propellants. The grains, which are made in a standard mold, are 1.79 inches in outside diameter and 3 inches long (single perforated) and weigh approximately 0.3 pounds. Throat areas can be readily changed so that this motor provides an expedient, low cost means of obtaining ballistic data.

No further effort was expended in attempting to refine the ballistic properties during Phase I, since it was felt that the formulation could be readily optimized to meet the requirements.

b. Physical Properties

Typical physical properties obtained with the above mentioned formulation are listed below:

Tensile Strength	3,000 + psi
Elongation, %	3.6 - 4.0
Modulus of Elasticity	125,000 psi

Density (approximately) 0.06 lbs/in^3

Because of the limited time available to investigate the castable combustible material, no further effort was expended on tailoring the physical properties. Further optimization was conducted under Phase II.

4. Design Concept

The castable propellant will be cast into a mold producing a shell which will have the same cross-sectional geometry as the finished core. Ten-foot-high sections will be cast and bonded together to obtain a full-length core.

5. Tooling Concept

A male and female mold will be fabricated of steel or aluminum plate and each will be made up of at least three longitudinal sections for ease of disassembly. A tapered insert will be placed between the sections of the inner mold to allow for extraction of the inner mold sections. The inner and outer molds will be bolted to a bed plate which will also serve as a means of transporting the loaded mold. All mold surfaces exposed to the core material will be Teflon[1] coated. A "spider" will be keyed into the tool column at the section interfaces. Hardwood shoes, coated with a release agent, will be used to position the sections at three or more starpoints.

Several methods have been considered for handling and lowering the finished sections into the motor. This aspect of the tooling will not be defined until the compressive strength and thread shear strength have been determined for the final formulation of the castable core material.

A longitudinal section of the mold and a cross section of the finished core configuration may be seen on Figures 81 and 82, respectively.

6. Processing Method

The following was envisioned as a workable process for fabricating a castable core.

1. Trademark of E. I. du Pont de Nemours & Co., Inc., Wilmington, Delaware.

a. After teflonin g, the mold sections will be assembled to each other and the bed plate. A casting "bayonet" will be inserted in each of the starpoints (6 for the configuration under consideration) to minimize the possibility of "bridging" in these thin sections. If this should become a problem, the tooling concept presented may be adapted to vacuum casting with some modification.
b. The cast propellant will then be cured step-wise. A tentative curing schedule is 2 to 4 hours at 140°F followed by 16 to 24 hours at 200°F. If curing agent "Z" is not used in the final formulation and some other curing agent is resorted to, this curing schedule may change somewhat.
c. After curing, the mold will be disassembled. The top edge of the section will be trimmed, if necessary, and lowered into the case and positioned around a spider at the forward end of the motor. The forward end of the first section will be sealed with a "potting" compound. Another spider will then be lowered down the tool column and positioned at the interface of the first and second sections. After applying combustible adhesive on the top edge of the first section, the second section will be lowered and positioned with another spider. This operation will be repeated until the required core length is built up.
d. The motor will be cast with propellant and cured.
e. The spiders and tool column will be removed.

7. Problem Areas

a. Problems inherent in "scaling-up."
b. Tailoring the formulation so as to maintain the elongation at 4 percent or greater and still comply with the requirements for tensile strength and modulus of elasticity. Although no major problem is envisioned, sufficient testing would have to be accomplished to confirm that the material meets the physical property requirements for this application.
c. Problems that may be encountered due to the limited amount of testing. Questionable areas have been anticipated and it is felt that since we are dealing with a true propellant, we will be able to find a ready solution.

E. EVALUATION OF CORE FORMING CONCEPTS

1. Areas of Evaluation

The following factors were considered, where applicable, in formulating a basis for evaluating the concepts which were investigated:

a. Cost reduction over current tooling.
b. Compatibility with propellant.
c. Compatibility with ignition.
d. Surface uniformity.
e. Ability to off-set hydrostatic head of propellant.

f. Ease of fabrication.
g. Ease of installation.
h. Ease of removal (if it must be removed).
i. Formulation of proper seal with propellant.
j. Storage and shelf-life.
k. Safety and hazard problems.
l. Adaptability to arrange in cavity geometry.
m. Tear resistance and permeability.
n. Chemical reaction.
o. Adaptability to scale-up.
p. Effect on ballistics.
q. Effect on cure and cool-down.

2. Weighing Factors

A list of comparison elements was prepared in order to establish a basis for comparing the various core forming concepts. These elements and their associated weights are shown at the left in Table XXXVIII. Point values were assigned to the various elements to be evaluated so that the total possible points for any processing technique is 1000. The elements that form the basis for comparison are further defined and amplified in Appendix F.

3. Evaluation Considerations

a. The evaluation was based on a core configuration similar to that used in fabricating motors such as the Thiokol 156-inch space booster.
b. Costs are based on the manufacture of 10 motors.
c. Utilities, handling equipment, design and tool column are not considered in cost.
d. Cost of facilities not normally a part of a space booster loading plant, and required for core fabrication, have been included.
e. Costs were generated from Thiokol related experience, budgetary vendor estimates and engineering judgment.
f. No attempt was made to apply a learning curve to the repetitive items of cost.

4. Method of Evaluation

The following core forming concepts were evaluated:

a. Collapsible core.
b. Membrane core.
c. Frangible core.
d. Laminated combustible core.
e. Castable combustible core.

The evaluation of concepts b, c and d, above, was a contractural requirement. The collapsible core was included in the evaluation because it had been fabricated and successfully used in the Thiokol 156-inch diameter space booster and, therefore, establishes a base for reference. The castable combustible core was introduced in the evaluation because combustible cores were of particular interest to the Air Force and because results obtained with the laminated core material had been erratic.

The costs (Item I in Table XXXVII) were accumulated by the Principal Investigator with the assistance of estimators and other personnel. The concept having the lowest cost was given the highest rating (total number of allowable points, 300). The ratio of the lowest cost to the next higher cost multiplied by 300, produced a numerical rating for the concept having the next higher cost, etc. The details of cost estimates for the various concepts are reported in Appendix G.

Comparison elements II through V in Table XXXVIII were evaluated by committee action in order to minimize bias and obtain a more equitable judgement in rating these various factors. The members of this committee were all experts in their fields, and they were knowledgeable of core forming techniques and other associated technology. The members, all of whom were employed at the Huntsville Division of Thiokol Chemical Corporation, were:

John L. Chambers	Chief, Motor Loading
W. I. Dale, Jr.	Program Manager [Contract AF33(615)-2998]
John Grider	Formerly Chief, Motor Processing at the Thiokol Space Booster Division, Brunswick, Georgia. Now at the Huntsville Division.
S. Paul Gualillo	Principal Investigator (Contract AF 33(615) -2998)
M. H. Larimer	Process Engineer on Frangible Core, Foams, etc.
J. L. Murphy, Jr.	Chief, Process Development Section
J. J. Webb	Group Leader, Process Engineering

The above-named personnel individually rated the various factors. Matters involving processing details, interpretation or other questions were discussed until the point in question was mutually agreed to or the question was satisfactorily answered. The individual scores were then averaged for the various elements and a numerical rating was assigned to each concept.

5. Results of Evaluation

The cost[1] of fabricating 10 motors for each of the concepts evaluated is:

1. These costs are only the costs that are dependant upon the concept used for core fabrication. Costs, such as propellant mixing, that are independant of the core concept, are not included in these estimates.

Collapsible Core	$1,205,163.00
Membrane Core	733,043.00
Frangible Core	315,115.00
Laminated Combustible Core	1,246,860.00
Castable Combustible Core	624,720.00

The cost rating was based on the above dollar value.

The rating for the comparison elements for each of the concepts is listed under the appropriate heading to the right of the comparison element in Table XXXVIII. Sub-totals are shown for the point values associated with various levels of the evaluation system outlined. The total point value, or rating, for each concept is listed at the bottom of the column associated with that concept.

Based on these total values or ratings, the result of the evaluation is as follows:

Concept	Rating	Evaluation Order	
Frangible Core	852	1	Highest
Collapsible Core	671	2	
Castable Combustible Core	603	3	
Membrane Core	431	4	
Laminated Combustible Core	418	5	Lowest

6. Discussion of Use Evaluation Results

The comments in the following discussion generally describe the reasons for which the evaluators graded the various concepts as they did. The comments are listed according to the item designations used in Table XXXVIII.

a. State-of-the-Art

(1) Present Feasibility of Concept (Total Point Value - 50)

The collapsible and frangible cores were both allotted the maximum number of points because feasibility has definitely been proven. The membrane core was assigned the lowest rating because feasibility has never truly been proven. An attempt to demonstrate feasibility on a small scale was unsuccessful. The castable combustible core has a slightly higher rating than the laminated combustible core because the basic structural material has demonstrated predictable ballistic performance that will meet the requirements. Further, its fabrication methods are based on current state-of-the-art.

(2) Degree of Reduction to Practice (Total Point Value - 50)

Again, the collapsible core was given the maximum rating because it has been successfully used in the manufacture of the Thiokol 156-inch Space Booster motor on which this entire evaluation is based in accordance with the contract scope of work.

Although feasibility has been proven for the frangible core, it was assigned a slightly lower rating because the demonstration motor was only one-fifth the size of the 156-inch motor. The membrane core was assigned the lowest rating because a test to prove feasibility of this concept was unsuccessful. Based on work performed at Picatinny Arsenal with small felted cores, a degree of proven feasibility was assigned to both combustible core concepts. The laminated combustible core shows a slight edge over the castable combustible core because thin cylindrical shells had been made at the time of this evaluation.

(3) Major Problems to Reduce to Practice (Total Point Value - 100)

As before, the collapsible core was assigned the maximum rating for reasons stated earlier. The frangible core was given a slightly lower rating because problems may be encountered in scaling up to five times the size of the motor used to prove feasibility. The membrane core was given a zero rating because it has the greatest number of major problems that must be overcome. The laminated combustible core rated considerably lower than the castable combustible core because of the complexity of the fabricating procedure and problems inherent in the structural material itself.

(4) Costs to Solve (3) (Total Point Value - 100)

These costs were not reduced to a dollar value. However, they generally reflect the ratings assigned in (3) above and establish a relative magnitude of costs.

b. Use

(1) Safety (Total Point Value - 25)

The safety aspects of both the core manufacture and use were considered. The collapsible core and the membrane core both were allotted almost the maximum rating. The frangible core was rated lower because of the proposed use of Class 7 explosives in the fragmentation network. Both combustible core concepts received relatively low ratings because both are propellants and are therefore subject to the hazards inherent in this class of materials. The laminated core received the lowest rating because of the required cutting and machining operations.

(2) Design Latitude (Total Point Value - 25)

The frangible core and the castable combustible core were allotted the maximum number of points because both can be cast to any desired shape. The laminated combustible core is limited to shapes that can be convolutely wrapped. Double web, anchor configurations, etc., would impose practical limitations on this process. It was therefore given only approximately 50 percent of the total possible points. The retraction of segments of a complex core configuration would impose severe limitations on the collapsible core. Therefore, it received a very low rating. The membrane core received an equally low rating, because this concept is only adaptable to straight sections of any given core configuration since tension has to be applied to the membrane linearly. Complex geometries such as double webs, anchors, etc. would be difficult to obtain.

In addition, any contouring of the forward or aft end of the core would have to be accomplished by the use of a rigid structure to supplement the membrane core straight section so that in essence a hybrid system would be required. The alternative, of course, would be to consider it for limited application only.

(3) Reliability (Total Point Value - 40)

Core manufacture, formation of proper core configuration, damage to grain, proper ignition and removability were considered. All but the membrane core received approximately 75 percent of the maximum rating since they were all unreliable to some degree in one or more of these areas. The membrane core received only 6 points because of the many attendant unresolved problems mentioned elsewhere in this report, which are associated directly or indirectly with most of the areas mentioned above. Principal weaknesses of the membrane core are lack of positive dimensional control and possible leakage of filler fluid.

(4) Ballistic Effects (Total Point Value - 30)

The collapsible and membrane core concepts were allotted 30 and 29 points, respectively, out of the allowable 30 points because in both cases, the mandrel is removed from the motor prior to firing. The membrane core was given one point less because it was felt that, if the membrane had to be left in place, even though ignition could be accomplished through it, some degrading ballistic effects might be experienced. The frangible core also rated relatively high since core removal would be accomplished simultaneously with ignition. Both of the combustible core concepts rated lower than the other three concepts because burning rates of the cores would seldom, if ever, match propellant burning rates. The laminated combustible core rated slightly lower than the castable combustible core because of the excessive number of interfaces the fabrication method creates.

(5) Vacuum Casting (Total Point Value - 10)

Considerations under this heading were whether vacuum casting could be directly used, not used, or used with modifications. The cost, or complexity, of any modification necessary to permit its use was also assessed. The collapsible core received the full number of points because it would present no problem. The membrane core system would not be adaptable to vacuum casting so it received zero points. The frangible core was given only 2 points because no data were available on the affect of vacuum on a foamed material. The castable combustible core is non-porours and may be adapted to vacuum casting so it received 0 points. The laminated combustible core received only 6 points because of the excessive interfaces in this core and the lack of data on the effect of vacuum on a laminated and porous structure.

(6) Inspection (Total Point Value - 30)

The core itself (5 points), surveillance during casting (5 points) and the grain surface after cure (20 points) were considered under this comparison element. The collapsible core received the maximum number of points because it can be completely inspected prior to use and because the propellant can be completely inspected after the core is removed. The membrane core was given a total of 24 points, most of the point loss being due to the problems that will be encountered in developing a method of inspecting the final core for leaks prior to casting. The frangible core, and the

combustible cores received approximately 10 points, each, because the grain surface cannot be inspected since the core remains in place.

(7) Grain Design Changes (Total Point Value - 5)

This evaluation dealt with modifications to an existing design. The collapsible core was allotted only 3 points because of the problems that would be encountered in machining heavy steel sections. The membrane core received the total number of points because it was felt that forward and aft template changes could readily be made. The remainder of the concepts all received 4 points because the attendant mold modifications could be made rather easily.

(8) Weights (Total Point Value - 25)

The collapsible and membrane cores both received 11 points because of the core weight itself in the case of the collapsilbe core, and the filler fluid that would have to be transported if grain support during storage is required in the case of the membrane core. The remaining concepts all received approximately 20 points because of the obviously lower weights involved.

(9) Cool-down (Total Point Value - 20)

The membrane core received the total number of points because a fluid recirculating system is already provided which could be used to recirculate cold well water to accelerate cooling.

The large mass of metal in the collapsible core creates a heat sink from which the heat must be dissipated through normal conduction and convection. Any attempt to accelerate the cooling would necessitate the use of auxilliary equipment. This concept, therefore, received only 15 points. The remaining concepts each received 12 to 13 points since these materials are all effective insulators and heat must be conducted out through the case wall.

c. Motor Storage (Long or Short Term)

(1) Grain Support (Total Point Value - 60)

Since the collapsible core is not left in place this concept would not provide any grain support and, therefore, received zero points. The membrane core received 43 points because the degree of support would depend somewhat on filler fluid settling effects; leaking of filler fluid would also be a danger. Both combustible core concepts were allotted the full number of points since they will provide adequate support for the grain. The frangible core received slightly less than the maximum number of points because of the lack of data or the ability of foamed materials to withstand sustained compressive loads.

(2) Compatibility of "Leave-in-Place" Materials (Total Point Value - 60)

Since the collapsible core is not left in place and compatibility would not be a problem, it received the maximum rating of 60 points. The membrane core received

33 points because small undetected leaks would present a compatibility problem with the propellant even for short term storage. Long term storage, even if possible, might (with filler fluid in place) present a compatibility problem with the case itself. The frangible core was allotted 39 points because data from prior work indicates that short term compatibility will not be a problem. Data are not available on long term compatibility, but we do not foresee this as a problem. Both of the combustible core concepts received a rating of 31 because of the lack of data on long term compatibility.

(3) Pre-launch Inspection (Total Point Value - 20)

The collapsible and membrane cores were allotted the maximum number of points because they may be inspected prior to launch. The frangible core and both of the combustible cores were given a zero rating since they will be left in place and will preclude inspection prior to launch.

d. Launch Site Effects

(1) Pad Damage (Total Point Value - 25)

Areas to be considered include damage from combustible or frangible fragments and leaking filler fluid. The collapsible and membrane cores received 25 and 24 points since it was not felt that blast damage would be any more severe than with motors fabricated with conventional cores. The castable combustible core was given a slightly lower rating (21) because in its cured state, it will be harder than normal propellants and any ejected matter could conceivably result in pad damage. The frangible core will eject pieces of foam. The amount of damage will be a function of fragmentation effectiveness. Because of this uncertainty, it was given a rating of 15. The laminated combustible core was given a rating of 16 because of the carbonized residue which was ejected during TX11 motor firings.

(2) Disposal or Return of Filler Fluid (Total Point Value -25)

The collapsible and combustible cores were given maximum, or near maximum, total points, because no material has to be returned to the manufacturing site. The membrane core was given 7 points because filler fluid will have to be returned. The frangible core was given 20 points because debris may have to be cleaned off the pad.

F. COORDINATION

Coordination meetings held between Air Force Materials Laboratory and Thiokol personnel during the course of these studies are discussed below.

Mr. John O. Snyder, technical manager of this program for the Air Force Materials Laboratory, visited Thiokol for a program review on 9 June 1966. During this meeting, the goals of the program were reviewed and progress was reported. Since it was apparent that only erratic results had been obtained with the laminated combustible core materials, samples of a previously developed "structural propellant" were shown to Mr. Snyder and it was suggested that a castable combustible core might be based upon similar compositions. Mr. Snyder agreed that the material appeared to hold promise and that the feasibility of this application should be investigated insofar as possible within the scope of the current contract. Permission was granted to evaluate this concept along with the others.

During this visit, the method of comparing the various tooling concepts was discussed and a list of weighing factors was agreed upon.

Messrs. W. I. Dale, Jr., and S. P. Gualillo of Thiokol Chemical Corporation made a trip to Wright-Patterson Air Force Base on 17 August 1966. Air Force attendees at the meeting were Messrs. John O. Snyder, Max Gunther, Charles Anderson, and Lt. H. S. Roey.

The Thiokol personnel presented an oral summary of the work that had been performed and the results that had been obtained. This summary included a detailed discussion of the evaluation of the following core forming techniques, which had been investigated under Phase I:

Collapsible Core
Membrane Core
Frangible Core
Laminated Combustible Core
Castable Combustible Core

Thiokol made two recommendations for continued work under the subject program. One of the recommendations consisted of a plan for further development of the frangible core concept. This recommendation was based on the superior ranking of this concept in the overall evaluation. The other recommendation consisted of a plan for development of the castable core concept. This recommendation was made because of the unique advantages offered by combustible materials and because this concept involves no detonable material. The collapsible core concept was not recommended for further study because it is considered to be a developed item and was included in the evaluation for comparative pruposes only.

G. PHASE I CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

a. Laminated Combustible Core

a. Motor firings conducted in Phase I have not produced any usable values for burning rate, characteristic velocity or other necessary ballistic properties.

b. The material is more difficult to ignite than the majority of Thiokol propellants.

c. If the original glaze is removed, due to the necessity of machining surfaces, the material becomes hygroscopic.

d. The behavior of the combustible core, in its current state of development, is erratic and different from normal solid propellants.

e. The exact mode of burning is still not understood. That is, it is not known whether the core material burns perpendicular to the laminates, parallel with them, or otherwise.

f. Motors with the same K_n operate differently. One motor will burst while another chuffs.

g. Chuffing occurs even at relatively high K_n values.

h. The mode of discharging solid residue out of the motor is not understood. It does not appear to be a gradual scarfing away of the surface. The residue may retain its structural integrity up to some point and may then be ejected in a mass great enough to offer nozzle restriction. All motors have had undesirable residue after firing.

i. The laminated combustible cores did not burn stably and reproducibily at K_n values normally used for the design of solid propellant rocket motors. It is concluded that because of one stable motor operation these cores are not satisfactory without improvements.

j. The greatest deterrent to this concept is its laminar structure which makes the material anisotropic. This manifests itself in dual burning rates and in properties both physical and thermal. Additionally it restricts the permissible latitude in core configuration.

k. The method as currently envisioned for fabricating a large core is complex and expensive.

b. Membrane Core

a. Creep (plastic flow) characteristics of organic films should be further confirmed under the full environment that the membrane will experience in the end application and should, therefore, be determined during the course of processing studies with short-length TX33 motors.

b. With the selected filler fluids, any undetected leaks in the membrane will inhibit propellant cure.

c. The membranes, in 2 mil thicknesses, were all permeable to some degree when tested with the selected filler fluids. If the thickness is increased to eliminate or reduce permeability, the film becomes unmanageable.

d. The laboratory testing of membrane materials can, at best, only serve as a guide in predicting their performance in a large scale application. The feasibility of this concept has not been proven to any substantial degree in Phase I.

e. The inspection of the finished core will require techniques that may have to be developed for this specific purpose.

f. It is felt that sufficient time and funds could overcome the many problems that this concept poses.

c. Frangible Core

a. Of the concepts which have been investigated, the frangible core is the only one whose feasibility has been demonstrated in a relatively large motor (approximately 1/5 the size of the 156-inch space booster).

b. Physical property values used in this design concept should be confirmed in any subsequent phase of this program.

c. Proposed fragmentation system should also be confirmed by tests to insure its effectiveness with the proposed higher density foams. Adequacy of delay periods to insure proper sequencing of starpoint fragmentation should also be confirmed.

d. Castable Combustible Core

a. The material is homogeneous.

b. It is non-hygroscopic.

c. Its behavior is predictable and reproducible within the limits of any standard solid propellant.

d. The material is easily ignited.

e. It may be cast to any desired geometry.

f. It may be fabricated using facilities common to any propellant plant.

g. The current formulation will have to be modified and tested to insure compliance with the established requirements of the combustible core.

h. For all practical purposes, the material is completely consumed when fired in a motor.

i. The many advantages of this combustible core material and the results obtained in limited testing warrant further development effort.

e. Evaluation

Based on the system of rating used, the concepts evaluated ranked in the following order.

1. Frangible Core
2. Collapsible Core
3. Castable Combustible Core
4. Membrane Core
5. Laminated Combustible Core

2. Recommendations

The following two concepts were recommended for consideration as continued effort on this program.

a. Frangible Core

This selection was based on the fact that it had the highest rating in the evaluation discussed in this report.

b. Castable Combustible Core

This concept was recommended for the following reasons:

It rated second in the evaluation of new concepts (the collapsible core, which actually rated second, was excluded because it had already been developed);

No detonable explosives were involved in this core forming technique;

It does not have to be removed.

At the conclusion of the above Phase I studies, the Air Force redirected effort on the program toward development of the castable combustible core concept, with special emphasis on the WS-120A system.

SECTION VI

PHASE II - CASTABLE COMBUSTIBLE CORE DEVELOPMENT

ACCOMPLISHMENTS

Effort under Phase II was directed towards establishing proof of principal for the selected process by engineering analysis and by tailoring specific materials and tooling to be used in the feasibility tests of Phase III.

A. ENGINEERING ANALYSIS

1. WS-120A System

a. Requirements

An analysis was made to determine the applicability of the castable combustible core to the WS-120A system as described in Air Force R.F.P. No. F4694-67-R-1023. The design constraints that were considered are based on the Thiokol TU-594 motor design and are listed below:

(a) The core must support the hydrostatic head of propellant prior to cure.

(b) The core must support itself during handling prior to use.

(c) The core-propellant combination must remain free from cracks and separation during cooldown, handling, storage and firing at 60°F.

(d) Vehicle acceleration must not exceed 15 g's.

(e) Launch tube pressure at silo exit must not exceed 400 psi.

(f) The pressure rise rate within the silo must not exceed 2,000 psi per second.

(g) The port geometry must not be altered.

(h) Vehicle velocity must be 100 to 300 feet per second at silo exit.

b. Evaluation

It was determined from this evaluation that the throat diameter would be 20.12-inch and the port diameter would be 22.9-inch. The inner diameter of the core must be larger than the diameter of the throat in order to prevent erosive burning with accompanying overpressurization of the motor. Additionally, the outer diameter of the core must be identical to the diameter of the propellant port. Consequently, 1.34-inch would be the greatest core thickness that could be used without erosive burning problems, and such problems might arise even with thinner cores.

In order to size the core as a structural member, buckling loads due to the hydrostatic head of uncured propellant were considered. The required core material modulus was calculated for several values of core thickness based on the following assumptions:

1. The core material is elastic and isotropic.

2. The core behaves as a very short cylinder with free ends.

3. The structural requirements for the core material can be based on buckling considerations; that is, the only ground handling load considered was the hydrostatic head of the propellant during the casting operation.

The maximum hydrostatic head of the propellant is 110 inches. For an assumed maximum propellant density of 0.065 lb/in^3, the maximum hydrostatic pressure is (110.0 x 0.065) = 7.15 psi. To provide a safe core design, the safety factor for elastic buckling should be at least 2.0. Therefore, the radius of the core for the TU-594 motor is 11.5 inches. The external pressure at which elastic instability will occur is given by[1]:

$$P = \frac{E}{4} \left(\frac{t}{r}\right)^3$$

Where:

P = external pressure (psi)
E = elastic modulus (compressive) - psi
r = radium of core (in)
t = core thickness (in)

Then:

$$Et^3 = 4\,Pr^3$$

$$= 4\,(15.0)\,(11.5)^3 = 91.250$$

The thickness and modulus combinations required to resist elastic buckling due to the hydrostatic head of the propellant are shown below:

Core Thickness (in)	Core Modulus (psi)
0.25	4.84 (10)^6
0.5	730,000
0.75	216,000
1.0	91,250
1.5	27,000
2.0	11,400

1. Flugge, W., Handbook of Engineering Mechanics, McGraw-Hill Book Company, Inc., New York, 1962.

From these results, it can be seen that the modulus required to resist buckling increases rapidly as core thickness decreases. As discussed above, erosive burning considerations dictate that the core must be less than approximately 1.0-inch thick; consequently, the modulus of the core must be greater than approximately 90,000 psi. (The required modulus would be less for motors of smaller diameter and/or shorter length.)

The modulus requirement for compatibility between the core and propellant at their interface was also investigated. The elastic solution for three concentric thick-wall cylinders of infinite length was used for calculating the bond stress between the core and propellant. The concentric cylinder model analyzed consisted of the case, propellant, and the core. The following assumptions were made in this analysis:

1. Small deformations;
2. Elastic, homogeneous and isotropic materials;
3. Plane strain (infinite length cylinder);
4. Propellant-core bond stronger than the cohesive strength at the propellant.

The low temperature storage requirements for the TU-594 motor is +60°F. At a storage temperature of +60°F, the relation between the sum of the principal stresses at the inner bore of the propellant grain and the core material modulus is shown on Figure 83. Based on previous experience, 1000 psi was estimated as the maximum allowable value for the sum of the principal stress in the propellant at the bond surface. For stresses higher than this value, failure would be expected in the propellant regardless of the bond strength between the core and propellant. In other words, the propellant-core bond was assumed to be stronger than the propellant. With this restriction for the allowable bond stress, the core modulus for a 1.0-inch thick core must not exceed 19,000 psi. For an 0.5-inch core thickness, the core modulus must not exceed 45,000 psi.

c. Discussion of WS-120A

It is obvious from the above evaluation that the modulus requirements, which evolve from the design constraints, are not compatible. For example, any core that would be thin enough to meet the ballistic requirements and stiff enough to resist the hydrostatic head of the uncured propellant would have a modulus high enough to crack the propellant during cooldown and operation at 60°F. This does not mean that castable combustible cores will not work in any propulsion system. It merely means that they will not work in the TU-594 base design with all of the design restraints that were imposed on the system. Directions in which design restraints could be changed to be compatible with castable combustible cores were clearly indicated. These were:

1. The web fraction of the motor could be decreased;

2. Internal support could be provided to the core during handling and prior to propellant cure;

3. The length of the motor could be decreased.

The first and second changes would be most helpful as far as the TU-594 is concerned. By decreasing the web fraction of the propellant, the thickness of the core would be less constrained by erosive burning, and propellant and core stresses and

strains would be reduced. By supporting the combustible core with a hollow metal shell, the requirement for a high core modulus would be eliminated and thus prevent critical propellant stresses during cooldown and motor operation. Decreasing overall motor length and diameter would generally lower propellant and core stresses; however, the effect on these stresses would be less than that which would result from a change in web fraction for the same change in ballistic performance.

Even though a castable combustible core could be designed for the WS-120A system if design details were changed as discussed above, this course of action is not recommended for the following reasons:

1. Motor loading density would be adversely affected.

2. If internal support were provided to the combustible core it should probably consist of a hollow metal shell, thus making the combustible core merely the secondary propellant in a bipropellant system. In such a case, there would be no need for the secondary propellant, or core, to have a high modulus; and, ideally, it would have the same modulus as the primary propellant.

3. The WS-120A system utilizes a cylindrical core which poses no removal problem.

d. Large Space Booster

In case the reader wonders why the castable combustible core concept is not feasible for the TU-594 motor after it was suggested for use in an even larger motor, this matter is discussed below:

The characteristics of the two motors are shown in Table XXXIX. From these data, it is obvious that in two critical areas the WS-120A is the more restrictive motor as far as the combustible core is concerned. The port-to-throat ratio of the Space Booster motor is more than 1.3 times as great as the port-to-throat ratio of the TU-594. Therefore, erosive burning would be no problem in the Space Booster motor, while it appeared to be a real problem in the WS-120A system. The web fraction in the Space Booster motor is only 0.326 of the web fraction of the WS-120A. This lower value vastly decreases the stresses and strains due to thermal contraction. Both of these differences arise from the high loading density of the WS-120A, and they more than offset the greater hydrostatic pressures that are present in the 85-foot-long Space Booster motor.

2. Structural Analysis of Demonstration Motor

Based on Thiokol's findings that the concept was not readily adaptable to the WS-120A system, the Air Force directed Thiokol to prove the concept in a small demonstration motor in lieu of studying another large motor system for feasibility of concept application. In view of this, an analysis was made of the core stability and the bond stresses at the interface of the combustible core and propellant. This analysis was made for a five-inch diameter "workhorse" motor, which is more fully described under Phase III of this report.

a. Stability Analysis of Core Material

In order to use the core as a structural member, it must be designed to withstand the hydrostatic head of the propellant during the casting operation. The required core material modulus was calculated for several values of core thickness based on the following assumptions:

1) The core material is elastic and isotropic.

2) The core behaves as a very short cylinder with free ends.

3) The structural requirements for the core material can be based on buckling considerations; that is, the only ground handling load considered was the hydrostatic head of the propellant during the casting operation.

The maximum hydrostatic head of the propellant is 12.0 inches. For an assumed maximum propellant density of 0.065 lb/in^3, the maximum hydrostatic pressure is (12.0 x 0.065) = 0.78 psi. To provide a safe core design, the safety factor for elastic buckling should be at least 2.0. Therefore, the core design should be based on a buckling pressure of 1.56 psi. The outside radius of the core for the five-inch motor is 1.5 inches. The external pressure at which elastic instability will occur is given by[1]:

$$P = \frac{\pi}{4} E \left(\frac{t}{r}\right)^3$$

Where:

P = external pressure (psi)
E = elastic modulus (compressive)
r = radius of core (in)
t = core thickness (in)

Then

$$E t^3 = 4 P r^3$$
$$= 4 (1.56) (1.5)^3 = 21.06$$

The core modulus to resist elastic buckling due to the hydrostatic head of the propellant is shown on Figure 84 as a function of core thickness for the five-inch motor.

b. Bond Stress Analysis Between Core and Propellant

The elastic solution for three concentric thick-wall cylinders of infinite length was used for calculating the bond stress between the core and propellant. The concentric cylinder model that was analyzed consisted of the case, propellant, and the core. The following assumptions were made in this analysis:

1. Small deformations;

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1. Flugge, W., Handbook of Engineering Mechanics, McGraw-Hill Book Company, Inc., New York, 1962

2. Materials are elastic, homogeneous and isotropic;

3. Plane strain (infinite length cylinder).

The low temperature storage requirement for the five-inch motor is +60°F. At a storage temperature of +60°F, the relation between the sum of the principal stresses at the inner bore of the propellant grain and the core material modulus is shown on Figure 85. Based on previous experience, 500 psi was estimated for the maximum allowable value for the sum of the principal stress in the propellant at the bond surface. For stresses higher than this value, failure would be expected in the propellant regardless of the bond strength between the core and propellant. In other words, the propellant core bond was assumed to be stronger than the propellant. The sum of the principal stresses in the propellant at the propellant-core interface is shown on Figure 85 as a function of core thickness for two values of core modulus. The data of this figure show that the sum of the principal stresses is 275 psi for a modulus of 10,000 psi and a core thickness of 0.375-inch. Using a safety factor of 2, the sum of the principal stresses becomes 550 psi, which is generally within the tolerable range. Also, based on the propellant and core configuration shown, it may be seen that for a modulus of 10,000 psi, the strain is calculated to be 2.7%. Using a safety factor of 2, the core material should have a strain of 5.4%.

c. Requirements of Demonstration Motor

Based on the above analysis, the following requirements (at 77°F) were recommended for the demonstration motor:

1) Core thickness - 0.375 in.

2) Core modulus - 10,000 psi

3) Tensile strength - 550 psi

4) Elongation - 5.4%

Since a safety factor of 2 was used in the above analysis, it may be seen that these requirements represent a very safe design and are based primarily on handling and manufacturing considerations.

B. CORE MATERIAL TAILORING AND CHARACTERIZATION

Tailoring of the castable combustible core material was initiated soon after analysis of the ballistic and physical property requirements of a core for the WS-120A system began. This was done for the following reasons:

1) The initial engineering analysis indicated that the WS-120A application would have drastically different requirements from the Space Booster application studied during Phase I.

2) It was difficult to set requirements for any of the parameters (i.e., modulus, extensibility, strength, burning rate, density, etc.) without knowing the general magnitudes of the others. Consequently,

engineering requirements and core materials had to be developed in an iterative process in which the results of each type of activity guided the work on the other type of activity.

Initial evaluation of the structural requirements indicated that the core should be about 1.75 inches thick and have the following properties:

Characteristic velocity (c*) ft/sec.	4500 (max)
Burning rate (r_b) in/sec. at 1000 psi	1.0
Density (p) lbs/in.	0.45 - .055
Modulus of elasticity, psi	8000 - 10,000
Elongation, %	30 (min)

These requirements were based on the properties that would be required to prevent propellant and/or core cracking when the motor was cooled and used at 60°F. Another consideration was the fact that an inch-and-a-half of core material had to be burned out prior to ejection of the missile from the silo.

Although it was recognized that the 1.75-inch core thickness for this specific motor would pose a ballistics problem, it was decided to study the problem further while initial core material mixes were being made with the approximate properties listed above.

Since the preliminary requirements differed widely from those for the Space Booster motor application, the core material formulation required more drastic modification than was originally anticipated. A total of thirty-six laboratory mixes were made in order to determine the ranges of properties that could be achieved with changes in binders, oxidizer, catalysts, cure time and temperature. The formulations and properties of these mixes are listed in Table XL and are identified by mix number in the discussion that follows.

Three types of binder systems were screened in order to select a binder system that would afford the physical properties required by this program. These were;

1) Polyester - imine (Mix Nos. 1-3)

2) Polysulfide (Mix Nos. 4-6)

3) Epoxide-amine (Mix Nos. 7-9)

Systems (1) and (2) exhibited adequate strain but did not meet the requirements for stress and modulus. System 3, which was plasticized with DOA, seemed to afford adequate stress and modulus but possessed very little elongation. Reinforcement of all systems with rayon gave noticeable increases in strength, but imparted erratic combustion properties to System 1.

The effects of catalysts (Mix Nos. 10-12) and microballoons (Mix Nos. 13-15) on burning rate and physical properties were investigated. It was determined that a

catalyst was needed in order to meet burning rate requirements. Small amounts of microballoons were found to have little effect on either physical properties or burning rate.

It was decided that System 3 possessed the largest number of desirable characteristics for this application and that some modification would possibly afford adequate elongation. It was found that a binder composed of mixed epoxides and cured with an amine afforded excellent physical properties when used with 20-micron ammonium perchlorate (Mix Nos. 16-21). Very slow burning rates were realized with low loading of ammonium perchlorate; therefore, it was determined that the ammonium perchlorate content should be at least 50%.

The burning rate requirement, however, could not be met using 20-micron ammonium perchlorate; therefore Mix Nos. 22 and 23 were made using 3.2-micron ammonium perchlorate in conjunction with ferrocene and larger amounts of microballoons to offset the density increase associated with higher loading of ammonium perchlorate. Mix No. 23 gave very favorable density and burning rate results; however, it appears that either the small ammonium perchlorate particle size, the microballoons, or some combination of effects, was decreasing strain.

Mix Nos. 24-29 were made in an effort to increase strain while maintaining the burning rate. Various concentrations of ammonium perchlorate and microballoons (a comparison of Mix Nos. 23 and 25 indicated that microballoons increase the burning rate) were utilized to no avail. A bimodal blend of oxidizer (Mix No. 30) and incorporation of plasticizer (Mix No. 31) also had little effect on strain. The use of n-butylamine as a chain stopper (Mix No. 32) lowered strain.

The test results of these mixes show that the incorporation of microballoons resulted in poor tensile properties, and that burning rate could possibly be increased by the use of larger amounts of catalyst.

Mix Nos. 33-35 were made in an attempt to increase propellant strain by the utilization of various stoichiometries of binder while holding the burning rate high with larger amounts of catalyst. Mix No. 36 incorporated N-aminoethyl-piperazine instead of the Shell curing agent. This substitution did not result in an enhancement in physical properties.

Additionally, tests of Mix No. 28 at 77°F showed the compressive strength and modulus to be 890 psi and 9,760 psi, respectively. This test was conducted in order to compare it to the modulus in tension, which was 12,594 psi at 77°F. Both samples were cured under the same conditions of time and temperature.

1. Processing

The end-of-mix viscosity was determined for every mix. As can be seen in Table XL, the viscosity varied from 1 to 208 kilopoise. Even though processibility of a propellant or core material is dependent upon the configuration into which it is to be cast and other parameters, end-of-mix viscosity can be used as a comparative indicator of the processibility of a propellant. As a rule of thumb, propellants for which the end-of-mix viscosities are less than 35 kilopoise can be processed with relative ease, and propellants having end-of-mix viscosities greater than 65 kilopoise will usually present significant processing problems. Propellants having end-of-mix

viscosities ranging from 35 to 65 kilopoise may present problems, but they can probably be processed by special means. According to these standards, most of the formulations that proved to be interesting can probably be processed in configurations for which their use is anticipated.

Difficulty was experienced in curing Mix No. 20. Full cure was never achieved. Mix No. 21 cured into an extremely hard mass (due to the high percentage of Epon 838) and was not given further consideration. Mix No. 24 was dry and too stiff to process. A two-step cure was used in Mix Nos. 25-30 and 32-36 in order to insure that the test samples were completely cured. It will be noted that when the sample is cured at a higher temperature or for a longer period, the elongation (strain) is degraded while modulus and strength are improved. Samples from the same mix and cure conditions show a decrease in all tensile properties when tested at elevated temperatures (140°F). The decrease is more pronounced for the modulus and strength than for the elongation.

2. Safety Tests

During the propellant tailoring work, sensitivity tests were conducted on three mixes that were typical of the more promising formulations to determine their suitability for further development. The results are listed below:

	Sensitivity		
Mix No. and Cure	Impact	Spark	Friction
23 (not cured)	neg. -250 Kg-cm	neg. -0.5 joules	neg. -6000 rpm
26 (cured)	neg. -126 Kg-cm	neg. -1.0 jouled	neg. -6000 rpm
28 (cured)	neg. -54 Kg-cm	neg. -1.0 joules	neg. -4000 rpm

These values are well within the limits of current state-of-the-art propellants. Because of these results and the fact that the formulations contain much less than 74% ammonium perchlorate, these formulations are considered to constitute a Class 2B processing hazards. Therefore, they are considered to be suitable for further development and use as far as processing safety is concerned.

3. Formulation Selection

Formulations 33 and 35 (Table XL) were selected for further characterization. Since the restraints imposed by the WS-120A system were no longer a consideration, the requirements for the demonstration motor allowed considerably more latitude in formulation selection. This made a number of formulations potential candidates for use as core material. Formulation 35 was of most interest because its modulus of 8,990 psi indicated that it would be stiff enough to support the hydrostatic pressure of the unused propellant in many rocket motors while its extensibility of 31.1% was the greatest of any formulation that was studied. This combination of properties results in a toughness that is attractive for structural applications. Formulation 33 was also chosen for further study in order to gain additional experience with a material of higher modulus. This material had the highest modulus (33,915 psi) that had been attained while retaining good extensibility (12.6%).

4. Characterization of Selected Formulations

The selected formulations (35 and 33) were scaled-up to 1-gallon mixes for further characterization. Both of these formulations contained 55% ammonium perchlorate, but were different in ferrocene content and in their ratios of EPON 871 and EPON 828. The 55% solids level was adequately low to afford excellent processibility with all fine particle ammonium perchlorate, which is desirable in the system to obtain a high burning rate. An extensive investigation of a formulation without a burning rate catalyst was not conducted because of the need for high burning rates. It was previously determined that formulations utilizing EPON 871 - EPON 828 binder systems had a pronounced dependency on solid loading in regard to tensile properties. Formulations containing 50 to 60 % solids were found to display workable strain values, while being sufficiently oxidized to offer relatively high burning rates. When the oxidizer level was higher, strain values fell off substantially and processibility decreased, especially when small particle ammonium perchlorate was used. It was also determined that bimodal blends of oxidizer offered little advantage in this system.

The ingredients of the two formulations that were selected for scale-up are given in Table XLI. Mix 12Q915 is a scale-up of Formulation 35, the high strain material, and Mix 12Q916 is a scale-up of Formulation 33, the high modulus material. Results of tests of these materials are given in the following paragraphs.

a. Processing Variables

Mixes 12Q915 and 12Q916 possessed very low viscosities (2.4 Kp at 120°F and 3.8 Kp at 80°F, respectively, at end-of-mix) and were mixed and processed with ease. Near the end of casting, however, some increase in viscosity was noted. The data of Figures 86 and 87 show that these materials have relatively short pot lives (approximately 2 hours) after addition of the curing agent. The viscosity increases that were noted are believed to be the beginning of cure and not thickening caused by temperature leveling. Soon after the addition of curing agent, a small temperature increase was observed and mixing was conducted under ambient conditions. The mixes were cured at 135°F for 24 hours followed by 170°F for 24 hours. The processing characteristics of both formulations are considered satisfactory for their intended use.

b. Safety Tests

The selected formulations are not considered as sensitive conventional solid propellants. Based on an evaluation of the ingredients of these formulations and safety test data, it was concluded that they should be considered Class 2B processing hazards. The results of sensitivity and stability tests performed on uncured and cured samples are given below:

	MIX 12Q915	
Test	Uncured Result	Cured Result
Impact (Kg-cm)	Neg. @ 250	Neg. @ 110
Spark (joules)	Neg. @ 0.025	Neg. @ 1
Friction (rpm)	Neg. @ 6000	Neg. @ 6000

MIX 12Q916

Test	Uncured Result	Cured Result
Impact (Kg-cm)	Neg. @ 250	Neg. @ 140
Spark (joules)	Neg. @ 0.025	Neg. @ 0.5
Friction (rpm)	Neg. @ 6000	Neg. @ 6000

This formulation did not burn when subjected to 240°F for 10 days.

The differences in spark sensitivity results obtained with uncured and cured samples are probably the result of manipulative difficulties associated with performance of this test on cured material. Spark sensitivity tests run on uncured materials are generally much more reproducible and are therefore considered more reliable. The higher impact sensitivity values of the cured materials are generally more reproducible than similar values for uncured materials and are therefore considered more reliable. The increased impact sensitivity of the cured materials can be accounted for by a lack of cushioning. Even though friction sensitivities were not different for uncured and cured materials within the range investigated (0-6000 rpm), it should be noted that similar formulations have been observed to be considerably more sensitive to friction in the cured state.

c. Ballistic Tests

A portion of each mix was cast into grains suitable for static testing in a TX405 motor (Figure 88). The grains were 3 inches long and had a 0.5-inch web thickness and an 0.75-inch center perforation. Four charges were loaded from Mix 12Q915 and five from Mix 12Q916. The 12Q915 charges were free of surface voids, but 12Q916 exhibited surface voids of moderate size in Charges 1 and 2, and smaller voids in Charge 4. The pressure-versus-time traces of these motor tests are shown on Figures 89-97, and a summary of the TX405 ballistic data is shown in Table XLII. These data show that there is no dependency of burning rate on pressure within the pressure range investigated. It is believed that this lack of pressure dependence, though unusual, is associated with the low oxygen-fuel ratio and the fine particle size of the oxidizer in these formulations.

It is also obvious from these graphs that Mix 12Q916 burns at a faster rate than Mix 12Q915. This result is inconsistent when compared with strand rates obtained from Mixes 33 and 35, in which Mix No. 35 burned faster. Mix 12Q915 is Mix No. 35 scaled-up with no variations except the use of slightly smaller ammonium perchlorate (2.2 micron instead of the previously used 2.8 micron). It was furthermore expected that Mix 12Q915 would burn faster since it contained 0.5% more burning rate catalyst (ferrocene). The surface voids displayed by some of 12Q916 charges are at least partly responsible for the higher rate exhibited by that formulation. It is quite possible that other voids were present under the propellant surface.

Strands burned from each mix gave a comparison with motor burning rates useful in correlating strand rates from other formulation studies with rates that could be expected in motors. The comparative burning rate data are shown on Figures 98 and 99.

Mixes 12Q915 and 12Q916 had average c* values of 3497 and 5551 ft/sec., respectively. Values of K_n versus pressure for each mix are shown in Figure 100; a linear correlation is shown if values at lower pressures are neglected.

d. Physical Properties

(1) Tensile Properties

JANAF specimens from each mix were tested both at ambient (77°F) and 140°F for tensile strength (ultimate stress), stiffness (modulus), and extensibility (strain at cracking and strain at maximum stress). Eight samples of each formulation were tested (four at each temperature). The results are given below. Each reported value is the average of four specimens.

MIX 12Q915

Test Temperature (°F)	Modulus (psi)	Strain at Cracking (%)	Strain at Max. Stress (%)	Ultimate Stress (psi)
77	10501	27.7	27.7	813
140	4736	11.2	11.2	404

MIX 12Q916

77	49085	10.9	10.9	2343
140	7709	14.3	14.3	732

It can be seen that the strain values for Mix 12Q915 are lowered by an increase in temperature. The most probable explanation for this phenomenon is post-cure since this type of propellant has been observed to stiffen somewhat during ambient aging. As shown above, the strain values for Mix 12Q916 increased at the higher temperature.

Agreement with previous observations concerning loss of strength at high temperatures may also be ascertained from these results. This problem, coupled with the probable post-cure, indicated that the optimum cure cycle for this propellant should be investigated further. Results of that investigation are discussed on Page 79 of this report.

(2) Compressive Strength

It was considered unsafe to apply sufficient compressive force to samples of these materials to crack them. Therefore, compressive moduli were obtained by compressing the samples 5% of their length. Three samples were tested for each formulation, and the results are given below. These values were taken as minima since the samples were of poor quality (not flat on the ends).

Mix No.	Test Temperature (°F)	Compressive Modulus (psi)
12Q915	77	7000
12Q916	77	18600

Since some doubt was raised as to the validity of these results because the ends of the samples were not absolutely parallel, it was deemed advisable to obtain verification by additional tests with samples prepared from Mix 12Q924. This mix, which was made for the cure cycle optimization study, was identical to Mix 12Q915 except for oxidizer particle size utilized. The results, which are listed below, correlate well with those obtained with Mix 12Q915.

Sample No.	Compressive Modulus (psi)
1	7300
2	7000
3	7200
4	6500
5	6960
6	7900
Average	7143

(3) Density

Density was measured in duplicate at 77°F using cured samples of each formulation. Results are given below:

Mix No.	Density (lb/in^3)
12Q915	0.0497
12Q916	0.0515

(4) Thermal Coefficient of Expansion

Constants for the coefficient of thermal expansion over various temperature ranges are given below:

Mix No.	Temperature Range (°F)	Coefficient of Thermal Exp. (in/in-°F)
12Q915	-40 to +10	5.51×10^{-5}
12Q915	+30 to +150	9.07×10^{-5}
12Q916	-50 to +20	4.53×10^{-5}
12Q916	+30 to +140	7.08×10^{-5}

Based on these data, the glass transition temperature for both binder systems is approximately +20°F.

(5) Shrinkage

Shrinkages during cure were plotted as Free Body Volume Changes (Figures 101 and 102). Volume decreased about 2% for both formulations when the uncured materials were subjected to 140°F for 2 days. This is considered a normal volume change for state-of-the-art propellants. As a basis of comparison, polysulfide propellants generally give a negative volume change of about 3% during cure; propellants with hydrocarbon binders give negative volume changes of approximately 1%.

(6) Compatibility with H-Series Propellant

Formulations 12Q915 and 12Q916 have been found to be chemically compatible with H-series propellant as exemplified by TP-H7036 propellant. This was evidenced in the peel and adhesion cup tests in which the core material was in intimate contact with TP-H7036 propellant. A visual examination of the interface after pulling the adhesion cups showed no evidence of chemical reaction or cure inhibition. Additionally, all of the raw materials in both the propellant and core material are, in themselves, compatible with each other.

(a) Peel Strength with H-Series Propellant

Attempts to measure peel strength of TP-H7036 propellant cured on the combustible core materials (12Q915, 12Q916) were unsuccessful. The combustible core materials (12Q915 and 12Q916) were cured, after which TP-H7036 propellant samples were cured in contact with the core materials. Attempts to peel the core material from the H-series propellant resulted in cracking of the core material end tabs when they were bent perpendicularly. These results indicate that the peel test is not applicable for the interface between conventional solid propellants and rigid structural materials.

It was anticipated that the peel test might not be applicable because of the stiffness of these core materials; therefore, adhesion samples were prepared concurrent with the preparation of the peel samples. The values obtained for adhesion are given below:

Mix No.	Test Temperature (°F)	Maximum Stress (psi)
12Q915		
12Q915	77	74.6
	140	37.9
12Q916	77	76.0
	140	45.5

Inspection of the tested samples indicated that tearing occurred at the bonds. The bond strength was lower than expected. However, when core materials were cured in contact with previously cured H-series propellant, an excellent bonding was achieved and applied stresses resulted in the tearing of the H-series propellant with the bond remaining intact.

It should be noted that samples on which the above-mentioned adhesion tests were performed were prepared from untreated combustible core material. The

surface of the core material was not treated in any manner prior to bonding. It is probable that a pretreatment could be developed to improve bonding of propellant to the core if such improvement proves to be required.

(7) Volumetric Compressibility

Volumetric compressibility was measured by the application of hydrostatic pressure to small samples of cured core material. The precision realized in this test did not justify the use of average values. Results, therefore, are reported for individual samples. Values reported are measured at a pressure of 2000 psi.

Mix No.	Test Temperature (°F)	Compressibility (%)
12Q915	77	1.72
	77	0.98
	140	1.76
12Q916	77	2.26
	77	1.55

5. Ignitability

Ignition tests were conducted on samples prepared from Mix 12Q915 to serve as a guide in sizing the pyrotechnic igniters that were to be used in the static testing of the demonstration motors in Phase III. A hot filament technique, similar to that employed for the laminated combustible core, was used in this test. The data for the core material were plotted (Figure 103) with data known for three other propellants in order to assess its relative ignitability. All of the propellants evaluated ignited fairly readily; however, it may be seen that the combustible core ignites even more readily than TP-H8047 and DTS-6149. On the basis of these data, it was believed that the combustible core would not present any ignition problems.

Based on the physical property, ballistics property, and processing data which were generated for Mix 12Q915, a decision was made to use this formulation in fabricating the cores for the demonstration motors. It was believed that no problems would be encountered with cores fabricated of this material.

6. Cure Cycle Optimization

As previously discussed, the tensile properties of Mixes 12Q915 and 12Q916 indicated that there was some doubt as to whether optimum cure had been achieved in the effect of cure time and temperature on the physical properties of the core material formulation which was selected for use in fabricating cores for the demonstration motors. A 1-gallon mix (12Q924) was made from which 36 JANAF tensile samples and 6 compression samples were case. This mix was similar to DTS-6381 (Mix 12Q915). The test results of the 6 compression samples are reported in the section on Compressive Strength.

The 36 JANAF tensile samples were divided into groups of four samples each. Two samples from each group were cured at 170°F while the remaining two samples

were cured at 200°F for specific time periods. The data obtained are presented in Table XLIII. It is apparent from these data that the cure condition of 72 hours at 170°F affords the optimum combination of stress and strain at ambient. Curing at 200°F for 72 hours was attractive because of the high strain value at 140°F; however, the lower strain value at ambient did not warrant the use of this cure cycle in lieu of 72 hours at 170°F. On the basis of these data, the cure cycle used in fabricating the cores for the demonstration motors was 72 hours at 170°F.

7. Short Term Aging Study

It was noted during the course of tailoring the core material that samples which were held in the laboratory appeared to stiffen after several days at ambient conditions. Since epoxide-amine resins have a natural tendency to post-cure, it was deemed advisable to conduct a limited aging study to insure that the core material properties did not undergo any radical change during storage. A 1-gallon mix (12Q926) of propellant was prepared in order to better define the short time aging characteristics of the core material. This formulation, as well as the one used in the cure cycle study (12Q924), utilized an oxidizer particle size of 2.8 microns as opposed to the 2.2-micron particle size used in Mix 12Q915. Forty JANAF specimens were cast from Mix 12Q926 and subjected to aging under various conditions. Strand burner samples were also cast and aged concurrently with some of the JANAF samples and burned at the completion of aging in order to determine if changes in burning rate would result from high temperature aging (due to possible loss of ferrocene).

Aging conditions, as well as tensile and burning rate data, are given in Table XLIV. Samples (A) were also tested at zero aging to define unaged tensile properties over a wide range of temperature. All samples were cured at 135°F for 24 hours plus 170°F for 72 hours.

The data shown in Table XLIV indicates that neither post-cure nor degradation is an appreciable problem. The aging included, in some cases, exposure to 145°F for one week to duplicate cure of the main propellant charge. Anomalous tensile data exhibited in some instances may be attributed to the use of JANAF molds which were handpacked. It should be noted that the burning rates are essentially constant in relation to both pressure and environmental conditions.

Tensile properties as a function of temperature are plotted on Figure 104. These data indicate that the tensile properties of this specific core material formulation are highly temperature dependent, with high strain being realized only from about 60 to 100°F.

C. CONCLUSIONS AND RECOMMENDATIONS

1. The ballistic and structural analyses indicate that the combustible core concept is not feasible for use with the TU-594 motor designed for the WS-120A system, but that it is feasible for a five-inch diameter demonstration motor.

2. Launch energy for the current WS-120A system from material within the motor could be achieved by tailoring the primary propellant grain accordingly or using a bipropellant grain with the secondary propellant having the same modulus of elasticity as the primary propellant.

3. A castable combustible core could be tailored for the WS-120A system if the web fraction of the motor were decreased and/or if the maximum motor length were decreased.

4. Core materials have evolved from this study which have a wide enough range in ballistic and structural properties to warrant their consideration in a variety of motor designs.

5. A formulation similar to the one used for Mix 12Q915 is suitable for use in fabricating cores for the five-inch demonstration motor.

6. The selected core material is:

   a. Safe to process and use

   b. Predictable and behaves ballistically in much the same manner as other propellants.

7. The core material has an effective burning rate exponent of zero, which presents some advantage in certain grain configurations.

SECTION VII

PHASE III - TX11-37 MOTOR DEMONSTRATION

ACCOMPLISHMENTS

The effort in Phase III was devoted to the fabrication, testing and evaluation of 5-inch-diameter motors which incorporate the castable combustible core. The objective was to demonstrate the feasibility of the castable combustible core concept.

A. MOTOR DESCRIPTION

1. Motor Hardware

The motor which was selected for use in demonstrating the feasibility of the castable combustible core concept was a Thiokol TX11 motor (Figure 105), which is a readily available heavy-walled test motor routinely used for batch testing of production lots of propellant. The motor case has an inside diameter of 5 inches and is 12 inches long. The forward and nozzle closures are sized to accommodate standard igniters and nozzle inserts. The overall length with a 12-inch long case is approximately 18 inches. The motor which is described herein is specifically referred to as the TX11-37. The -37 designates the particular configuration that utilizes the combustible core.

2. Grain Configuration

The grain utilized in the TX11-37 motor is essentially a bipropellant grain having a cylindrical configuration. The core has a 0.375-inch web while the propellant has a 0.9-inch web. This grain design evolved from the analysis which was made and reported under Phase II. Since the grain is a radial burner and is inhibited on both ends, the resulting pressure trace is progressive.

3. Igniter

The igniter that was used is a modified Thiokol TX96-2 igniter. This igniter has the same external configuration and size as that shown on Figure 64 which was used to ignite the IITRI laminated combustible core motors. The basic difference is that the TX96-2 igniter uses a charge of only 10 grams of TICI composition (boron-potassium nitrate pellets), in lieu of the composition listed on Figure 64 and, therefore, has a much lower heat flux. The void resulting from the difference in charge volume is filled with a foamed plastic plug.

B. CORE PROCESSING AND TOOLING DEVELOPMENT

The general procedure used in fabricating the demonstration motors consisted of prefabricating the combustible cores, locating them within the TX11 motor cases, and bottom casting the propellant around them.

A 2-1/4-gallon mix of core material was made using the same formulation as Mix 12Q915, which was characterized under Phase II. The actual composition is shown in Table XLI. This mix (F-1642A) represented the first major "scale-up."

The tooling used for casting the cores consisted of split molds that are held together with hose clamps. This cylindrical assembly is then retained between a base plate and a top retaining ring by the use of tie rods. A sectional view of the core mold assembly may be seen on Figure 106. Four sets of molds were fabricated so that all the cores could be cast out of the same mix and thus insure uniformity of composition and processing.

After mixing, the core material was deaerated using a slit plate, and it was then "bayonet cast" into each of the molds to a depth that represented a slightly greater volume than that of the finished core. The material was quite fluid and had an end-of-mix viscosity of 0.96 kilopoise. A mandrel (Figure 107) was then inserted through the top retainer and grain former ring until it centered itself by means of the centering cone located on the end of the mandrel. The mandrel was then held in place with knurled knobs (Figure 106). The excess core material was allowed to exude through sixteen bleed holes in the Teflon grain former ring. These castings were then cured in accord with the cure cycle that evolved from the cure study for this material (24 hours at 135°F plus 72 hours at 170°F). The core casting fixture was then disassembled and the cores were X-rayed. Numerous fine voids were revealed in the X-rays. The voids were attributed, at least in part, to improper deaeration resulting from agglomerated oxidizer. Since there was a possibility that these voids might result in overpressure of the motors during static test, another 2-1/4-gallon mix (F-1647A) was made and four more cores were cast. In an effort to insure that the cores would be void free, the mixing procedure was changed so that the ingredients were added to the mixer in smaller increments with just enough binder to wet the solids. This permitted intimate mixing and no agglomeration of the oxidizer. Additionally, vacuum was applied to the mixer during the last 10 minutes of mixing. A much finer slit plate (1/32-inch) was used in deaerating this mix than was used in the previous mix. Radiographic inspection revealed that these cores were void free. Cooling cracks in the extreme ends of the cores were trimmed off prior to use.

C. MOTOR MANUFACTURING

Four TX11-37 demonstration motors were fabricated using existing TX11 bottom casting fixtures with a modified casting sleeve. These motors were bottom cast because there was insufficient room between the core and the lined case to permit bayonet casting, which would have simplified the casting operation. When using bottom casting fixtures, the metal core also acts as a check valve for the propellant. For this reason, the combustible cores had to be assembled on a fixture that resembled the metal core. The assembled core is shown on Figure 108. Since the combustible core will withstand the hydrostatic head of the propellant, all that would be required for its use in most other motors would be to affect a bottom seal between the core and the case and provide a means of positioning it within the motor. The assembly of the core within the casting fixture may be seen on Figure 109.

The motors were cast using Thiokol propellant TP-H7036. This HC propellant was selected because it is performing well in TX354 motors for the Air Force. The loaded 5-inch-diameter motors were then cured for 7 days at 145°F. After cure, the propellant was "cut-back" at both ends of the motors so that it was flush with the ends of the cores, and the motors were X-rayed. The X-rays did not reveal any unbond or void at the interfaces of cores and propellant. This was further confirmed by a visual inspection of both ends of the motors after cut-back. The X-rays did, however, reveal a sub-surface void in one end of Motor No. 1. This void was located close to the surface

of the TP-H7036 propellant so that it was easily inhibited and caused no problem. Motor No. 3 had several small voids in the propellant which we did not feel were any cause for concern.

The forward and aft ends of the demonstration motors were inhibited with an elastomeric material (TA-L723B) in order to insure that propellant ignition was initiated only at the core-propellant interface. Motor assembly was completed by threading a forward closure and nozzle onto the case. The final assembly may be seen on Figure 105.

D. TX11-37 MOTOR TESTS

The test set-up for the static testing of the assembled motors may be seen on Figures 110 - 117. Color movies at 64 frames per second were also taken of each test.

The static testing of these motors proceeded in a normal fashion, with the following exceptions:

a. The nozzle separated from the case in Motor No. 1. This occurred at 1100 psi, after the propellant had burned through approximately 75% of the web. The nozzle separation was not caused by overpressurization, and it is attributed to faulty threads. For purposes of this test, the nozzle failure was irrelevant since the propellant was almost consumed and the pressure-time trace up to the point of failure was generally similar to the other motor firings and did not affect the test objectives.

b. A "burn through" occurred at the nozzle-case threaded joint. This burn through was apparently caused by a faulty gasket seal. The test results were not noticeably affected by it.

c. A perceptible ignition delay between the core and propellant was noted both visually and audibly. This was later confirmed in the pressure-time traces.

An examination after disassembly revealed that the motors had burned "clean" and no residue remained except in Motor No. 1, which had a slight trace of carbonized residue. This was due to the fact that there was still a small amount of propellant left in the motor that burned at atmospheric pressure after the nozzle blew off.

The pressure-time traces for Motors No. 1, 2, 3, and 4 are shown on Figures 118, 119, 120, and 121, respectively, and the pertinent data are summarized in Table XLV.

1. Test Evaluation

a. Ignition of Castable Consumable Cor :

The calculated heat flux in the motor port from the TX96-2 igniter was 10.9 btu/in^2-sec. This is an average value of heat flux during the time interval between first indication of pressure in the motor and the attainment of 100 psia chamber pressure, and it is a typical value for this type ignition system and motor configuration. The ignition times and pressure rise rates for the four motors (Table XLVI) were satis-

factory and as expected for the heat flux produced by the igniter. This confirms the earlier hot wire tests, which indicated that the ignitability of the core material is at least comparable to that of TP-H8047, TP-H7040 and DTS-6149 propellants.

b. Ballistic Performance

The predicted and measured performance data from the four TX11-37 motor tests are shown in Table XLVII. The predicted values for core material burning rate and characteristic velocity were based on data taken from tests of TX405 motors. The TX405 motors were not loaded from the same mix (F-1647A) from which the cores for the TX11-37 motors were cast; however, strand data from this mix confirms the predicted rate shown in Table XLVII. The burning rates of the cores obtained from the TX11-37 tests correlate quite well with those obtained from the TX405 static tests; however, the strand data is approximately 0.2-inch per second higher than the rate obtained in the motor static tests.

The measured characteristic velocity is higher than that measured in TX405 motors; however, the TX11-37 value is based on an average throat area for the entire motor operation. Actual throat area during core burning is unknown, but it is thought to be less than reported which was the average of before-and-after throat areas. Therefore, the values of characteristic velocity listed in Table XLVII for the four TX11-37 tests may be higher than actual. Propellant density used for the predictions (0.0497 lbm/in^3) may have been lower than actual since the density of the core material used in the TX11-37 motors was not measured. As a result of the lower burning rate, the average pressure was lower than predicted.

Each pressure-time plot of castable consumable core operation is characterized by a plateau which lasts for approximately the final 0.15-second of burning time. This trace shape is not entirely consistent with the predicted pressure-time trace, which was uniformly progressive throughout web burning time. Although the plateau could be attributed to any one of several factors, the most probable cause is that the as-cast core interface surface was polymer-rich and the burning rate of this polymer-rich film was lower than the burning rate of the remaining core.

c. Core-Propellant Transition

The pressure-time records of the TX11-37 motors are characterized by a transition period between the core burning and the propellant burning during which the chamber pressure returned to zero. This may not actually have been the case since the pressure cells are calibrated for accuracy primarily within the anticipated operating pressure range, and it is quite conceivable that there was some residual pressure when the instrumentation indicated zero. The duration and pressure rise rate for ignition of the propellant during this transition period are shown in Table XLVIII. The most probable explanation of the delayed propellant ignition is polymer enrichment (or commonly, oxidizer impoverishment) on both the core and propellant as-cast surfaces. Propellant surfaces of most cast motors are polymer-rich in varying degrees; however, the igniter provides some turbulence and a sustained energy output that is sufficient to pyrolyze the thin polymer layer and ignite the propellant. It is reasonable to assume from the pressure-time traces that the core burned through uniformly, but at a much reduced rate through the polymer-rich core outer surface. The propellant surfaces would then be exposed simultaneously and the heat from the burned core gases would be insufficient to effect rapid ignition of the polymer-rich propellant.

d. Suggested Solutions to Core-Propellant Transition

A number of solutions, which singly or in combination, should reduce the ignition delay to within tolerable limits are discussed below:

1. Polymer enrichment at the as-cast surfaces is a greater problem in the core than in the propellant. The propellant has a higher oxidizer content than the core and should, therefore, tend to produce a thinner polymer-rich film. Additionally, the HC polymer is more readily burned than the epoxy resin that is used as a binder in the core. This suggests the possibility of incorporating some HC polymer with the epoxy binder and/or increasing the oxidizer content of the core. These changes would have to be reconciled against acceptable core material properties.

2. It was found in motor tests with IITRI core material in Phase I that a long ignition delay was not experienced in spite of the unbonded condition at the core-propellant interface. The cores, however, were all, of necessity, machined on their outer surface to control the outside diameter (due to the mandrel wrapping technique that was used). This exposed virgin core material had a high oxidizer content. On the basis of this, the castable combustible core could be treated in any one of the following ways:

   a. Machine the as-cast outer surface of the castable combustible core to an estimated depth of 0.030-inch

   b. Machine longitudinal grooves or flutes on outer surface

   c. Discreetly dimple the outer surface

   The depth of cut in (a), (b), and (c), as well as the area of (b) and (c), would have to be determined empirically. If deemed necessary, the grooves or dimples could be "buttered" with a high heat output pyrotechnic mix to insure good ignition.

3. Polymer enrichment appears to be aggravated by bottom casting. The cores, although displacement cast, created the same effect as bottom casting since the core material had to sweep-up along the walls of the mold. The propellant was bottom cast. It is believed that bayonet casting would result in a thinner polymer film.

4. Chemical treatment of the surfaces might offer a solution; however, this is not recommended since it could involve considerable research.

E. CONCLUSIONS AND RECOMMENDATIONS

1. Fabrication of the TX11-37 motor did not present any unusual problems.

2. The cores adequately withstood all of the mechanical loads experienced during the entire life of the motors.

3. All of the cores performed in a uniform and identical manner.

4. The motors performed, generally, as expected except for the excessive core-propellant ignition delay.

5. Prior to any eventual application of this concept, a study should be made to confirm remedial measures for insuring adequacy of core-propellant ignition. The use of a "window bomb" in this study would be expedient and is highly recommended.

SECTION VIII

PROGRAM CONCLUSIONS AND RECOMMENDATIONS

Conclusions drawn and recommendations made as a result of the work performed under this program are given below.

1. Based on the rating system that was used, the evaluated concepts are ranked in the following order of suitability for the manufacture of large Space Booster size rocket motors:

Frangible Core	1 (Best)
Collapsible Core	2
Castable Combustible Core	3
Membrane Core	4
Laminated Combustible Core	5 (Worst)

2. Rigid combustible cores are not compatible with the TU-594 base design for the WS-120A missile with all of the design restraints that were imposed on the system. Ways in which the restraints could be changed to make the castable combustible core compatible with the WS-120A system are:

   a. The web fraction of the motor could be decreased;

   b. Internal support could be provided to the core during handling and prior to propellant cure;

   c. The length of the motor could be decreased.

   These changes are not recommended for the WS-120A system because they would decrease the efficiency of the motor without providing offsetting advantages for that particular system.

3. Castable combustible cores can best be used in motors of moderate length and/or web fraction.

4. Castable combustible cores may be most effectively used in motors that employ a core shape of such complexity that core removal is difficult and with grain configurations that are not already limited by propellant mechanical strain.

5. In motors where propellant slump (in storage) may present a potential problem, the combustible core may afford an effective solution if the motor design is within the necessary constraints of web fraction and/or motor length.

6. The feasibility of using combustible cores must be evaluated for each specific motor design for which they are considered.

7. It is recommended that a study program be conducted to resolve the core-propellant interface problem prior to use of the castable combustible core concept for a specific motor design.

8. Future work with the combustible core concept should consider temperature cycling of motors prior to static testing.

9. The castable combustible core materials that were studied are representative of a broad family of rigid combustible materials. By simple variations in ingredients these materials can be tailored to have wide ranges of physical and ballistic properties. Consequently, they should be considered for use in any application where rigid combustible materials are required.

10. The castable, combustible core material that was developed has a burning rate coefficient of pressure that is nearly zero. Consequently, materials of this type should be considered for any application in which minimum pressure sensitivity of burning rate is of prime importance.

BIBLIOGRAPHY

Heilbron, I., et al, Dictionary of Organic Compounds, Volume Nos. 1 through 4, Oxford University Press, 1953.

Hodgman, C. D., Handbook of Chemistry and Physics, Chemical Rubber Company.

Honig, J., et al, The Van Nostrand Chemist's Dictionary, D. Van Nostrand Company, Incorporated, New York

Kirk, R. and Othmer, D., Encyclopedia of Chemical Technology, The Interscience Encyclopedia, Incorporated, New York.

Lange, N. A., Handbook of Chemistry, Tenth Edition, McGraw-Hill Book Company, Inc., New York, 1961.

Perry, J. H., Chemical Engineer's Handbook, Third Edition, McGraw-Hill Book Company, Inc., New York, 1950.

Sax, N. I., Dangerous Properties of Industrial Materials, Second Edition, Reinhold Publishing Corporation, 1963.

Schefland, L. and Jacobs, M., Handbook of Solvents, D. Van Nostrand Company, Incorporated, New York.

Sneed, M. and Maynard J., General Inorganic Chemistry, D. Van Nostrand Company, Incorporated, New York.

Technical Bulletin, SC:64-52, EPON Resin 871, Shell Chemical Company

Technical Bulletin, SC:60-146R, EPON Resin 828, Shell Chemical Company

TABLE I

PROPERTIES OF MEMBRANE MATERIALS

Material Designation	Type Material	TENSILE STRENGTH (psi)		ELONGATION (%)		TEAR STRENGTH (Initial-Gms) GRAVES		TEAR STRENGTH (Propagated-Gms) ELMENDORF		BURST STRENGTH (psi)	DIMENSIONAL CHANGE (%) (30 min at 300°F)	
		MD	TD	MD	TD	MD	TD	MD	TD	MULLEN	MD	TD
ASTM Test Method		D-882-61T	D-882-61T	D-882-61T	D-882-61T	D-1004-61	D-1004-61	D-1922-61T	D-1922-61T	D-774-63T	D-1204-65	D-1204-65
CELANAR (1 mil)	Polyester	30,000 ult		96 ult		1,135		27		80	-1.2	
ACLAR 22A (1 mil)	Fluorohalo-carbon	8,000-11,000	4,000-6,000	50-150	200-400	270	150	16	29	31	+11	
(5 mil)		5,000-7,000	4,000-6,000			1,890	1,798			68	+25	
ACLAR 22C (1 mil)	Fluorohalo-carbon	6,000-8,000	5,000-7,000	50-150	50-150	370	320	12	18	23	2	2
(5 mil)		6,000-8,000	5,000-7,000			2,300	2,340			66	2	2
ACLAR 33C (1 mil)	Fluorohalo-carbon	8,000-11,000	6,000-8,000	50-150	50-150	410	410	8	26	23	2	2
(5 mil)		6,000-8,000	6,000-8,000			2,506	2,660			73	2	2
CAPRAN 77C (1 mil)	Polyamide	9,000-12,000	10,000-13,000	350-400	400-500	500-600	470-520	50-90	50-70	Neg. to 18	2	2
VAC-PAK H.S. 8171	Vinyl	14,000-16,000		200				50			1	
VAC-PAK A-126	Vinyl	13,000-17,000		200				50			0.5	
SCOTCHPAR (1 mil)	Polyester	12,000-25,000 (yield) (break)		120		1,135				75	1-2	
RHINO 55	Reinforced(nylon) Polyethylene	1,900-5,000		260-600						85		
TEFLON	FEP Fluorocarbon	1,700-3,000 (yield) (ult)		300		270		125		11	+0.7	-2.2
MYLAR-Type A (1 mil)	Polyester	12,000-25,000 (yield) (ult)		120		600		15		66	2.3	
MYLAR-Type T (1 mil)	Polyester	40,000 (ult)		50		450		12		55	2-3	
TEDLAR-Type 20	Polyvinylfluoride	6,000-19,000 (yield) (ult)		110		452		12		70	7	
TEDLAR-Type 30	Polyvinyl-fluoride	5,000-13,000 (yield) (ult)		190		542		22		37	4	

TABLE I (cont'd)
PROPERTIES OF MEMBRANE MATERIALS

Material Designation	Type Material	TENSILE STRENGTH (psi)		ELONGATION (%)		TEAR STRENGTH (Initial-Gms) GRAVES		TEAR STRENGTH (Propagated-Gms) ELMENDORF		BURST STRENGTH (psi)	DIMENSIONAL CHANGE (%) (30 min at 300°F)	
ASTM Test Method		MD D-882-61T	TD D-882-61T	MD D-882-61T	TD D-882-61T	MD D-1004-61	TD D-1004-61	MD D-1922-61T	TD D-1922-61T	MULLEN D-774-63T	MD D-1204-45	TD D-1204-45
TEDLAR-Type 40	Polyvinyl-fluoride	5,000-10,000 (yield) (ult)		260		634		48				
HERCULITE 80	Reinforced (nylon) Vinyl	295 (warp)	305 (fill)			105 (warp)	115 (fill)					
HERCULITE F-36	Reinforced (nylon) Vinyl	295 (warp)	305 (fill)			105 (warp)	115 (fill)					
HERCULITE F-44	Reinforced (nylon) Vinyl	220 (warp)	220 (fill)			70 (warp)	72 (fill)					
HERCULITE 20	Reinforced (nylon) Vinyl	115 (warp)	100 (fill)			37 (warp)	37 (fill)					
HERCULITE 6	Reinforced (nylon) Vinyl	84 (warp)	80 (fill)			35 (warp)	35 (fill)					
VELOSTAT (4 mil/side)	Conductive, nylon reinforced poly-ethylene	7,000										

TABLE II

PROPERTIES OF GENERAL CLASSES OF PLASTIC FILMS

Type Material	Tensile Strength (psi) MD	Elongation (%) MD	Tear Strength (Propagated-gms) ELMENDORF MD	Burst Strength (psi) MULLEN	Dimensional Change (%) (30 min at 300°F) MD
Acrylonitrile Styrene Copolymer	10,000-15,000	20-60		40-60	40
Cellulose triacetate	9,000-16,000	10-40	4-10	50-70	0 to 0.8
Polyurethane elastomer	7,000- 9,000	550-650			
Ethyl cellulose	8,000-10,000	20-30	7-36	50-85	0 to 0.7
Polytrifluorochloro-ethylene copolymer	5,000- 8,000	50-150	10-26	42 (2 mil)	2 to +15
Low density polyethylene	1,250- 2,500	200-700	100-300	10-12	
High density polyethylene	2,400-6,100	10-650	15-300		
Polytetrafluoroethylene	1,500- 4,000	100-350	10-100		
Polycarbonate	8,400-10,500	85-110	10-16	25-35	0
Vinylidene Chloride-vinyl chloride copolymer	8,000-20,000	35-110	10- >100	25-35	
Regenerated cellulose (cellophane)	7,000-18,000	10-50	2-20	55-65	-0.7 to -3

SOURCE: Modern Plastics Encyclopedia - 1965, McGraw-Hill Inc., New York, N. Y.

TABLE III

COST OF MEMBRANE MATERIALS

Material	Roll Size	Roll Cost	Cost/sq. ft.
MYLAR A (3 mil)	36" x 1700'	$ 167.40	$ 0.033
(5 mil)	36" x 1000'	167.40	0.056
FEP TEFLON C (5 mil)	36" x 960'	1,782.00	0.600
(10 mil)	36" x 480'	1,782.00	1.200
Rhino 55	36" x 100'	15.00	0.050
	25,000 sq. ft.	875.00	0.035
CELANAR (2000) (3 mil)	36" x 1700'	167.40	0.033
(5 mil)	36" x 1000'	167.40	0.056
VELOSTAT	36" x 150'	242.50	0.540
SCOTCHPAR (30G2004) (3 mil)	36" x 1700'	167.40	0.033
VAC-PAK HS-8171 (5 mil)	36" x 1110'	540.00	0.164

TABLE IV

MEMBRANE MATERIALS

Trade Name	Type	Thickness[a] (mils)	Vendor
Mylar	Polyester	2	E. I. duPont deNemours & Co., Inc.
Rhino #55	Nylon reinforced polyethylene	3	Raven Industries, Inc.
ACLAR 22-C	Fluorohalocarbon	7	Allied Chemical
CAPRAN 77C	Polyamide	1	Allied Chemical
CELANAR 2000	Polyester	4	Celanese Plastics Co. (A division of Celanese Corporation of America)
VELOSTAT	Reinforced polyolefin	20	Custom Materials, Inc.
H-Film	Polyimid	2	E. I. duPont deNemours & Co., Inc.

(a) Thickness of film actually used in tests.

TABLE V

MEMBRANE - FILLER FLUID EVALUATION DATA

MEMBRANE MATERIAL	MEMBRANE MATERIAL PHYSICALS PRIOR TO COMPATABILITY TESTS			FILLER FLUID STANNIC CHLORIDE/WATER ($SnCl_4$)			FILLER FLUID ZINC CHLORIDE/WATER ($ZnCl_2$)			FILLER FLUID ETHYLENE DIBROMIDE/ETHYL ALCOHOL ($C_2H_4Br_2$)				
	Ult. Stress (psi)	Strain @ Max. Stress (%)	Strain @ Breaking (%)	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (psi)	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (psi)	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (psi)	Yield Stress (psi)	Yield Strain (%)
MYLAR A	26,066	152	152	19,695	141	11,534	21,195	134	10,067	23,327	179	4,400		
RHINO #55	4,722	357	357	1,500	274	304	1,267	371	267	DELAMINATED				
ACLAR 22-C	5,165	17	90	2,608	10	2,383	2,563	10	2,158	Exceeded Mechanical Limits Of Machine 1,543	605	935	1,270	17
CELANAR 300 SERIES/2000	27,146	151	151	25,125	165	12,650	21,110	158	11,558	21,053	167	5,147		
CAPRAN 77C	9,839[b]	364	389	DISSOLVED			DISSOLVED			PARTIALLY DISSOLVED				
VELOSTAT	5,694	31	50	416	28	135	350	27	148	1,082	40	92		
H-FILM	28,420	102	102	30,075	102	11,525	24,050	55	8,038	25,236	132	7,200		
COST OF FILLER FLUIDS (COST/LB OF SOLUTION)				$3.17[a]			$0.23[a]			$0.92				
COMPOSITION & SPECIFIC GRAVITY OF FILLER FLUIDS				80.7% $SnCl_4$ 19.3% Water 1.741 gm/cc @ 28.5°C			66.79% $ZnCl_2$ 33.21% Water 1.756 gm/cc @29°C			86.32% $C_2H_4Br_2$ 13.68% C_2H_5OH 1.780 gm/cc @26.7°C				

a. Price does not include cost of water

b. Not in agreement with vendor literature

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TABLE V

MEMBRANE - FILLER FLUID EVALUATION DATA

MEMBRANE MATERIAL	FILLER FLUID ZINC BROMIDE/WATER ($ZnBr_2$)					FILLER FLUID STANNOUS CHLORIDE/WATER ($SnCl_2 \cdot 2H_2O$)					
	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (psi)	Yield Stress (psi)	Yield Strain (%)	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (psi)	Yield Stress (psi)	Yield Strain (%)	
MYLAR A	32,800	152	12,914	19,333	8	21,165	111.4	12,914	14,106	10	
RHEMO #55	2,033	234	. 773		234	2,423	373	786			
ACLAR 22-C	4,680	10	4,267	1,333	49	5,204	9	4,710	3,479	27	
CELANAR 300 SERIES/2000	24,221	154	12,488	14,700	10	26,578	142	15,201	17,038	10	
CAPRAN 77C	PARTIALLY DISSOLVED					DISSOLVED					
VELOSTAT	407	23	103			283	24	71			
H-FILM	26,525	1,095	7,806			19,816	61	8,298			
COST OF FILLER FLUIDS (COST/LB OF SOLUTION)	$0.37					$1.99[a]					
COMPOSITION & SPECIFIC GRAVITY OF FILLER FLUIDS	69.63% $ZnBr_2$ 30.37% Water 1.766 gm/cc @ 25°C					70.92% $SnCl_2 \cdot 2H_2O$ 29.08% Water 1.779 gm/cc @ 26.6°C					

TABLE V

MEMBRANE - FILLER FLUID EVALUATION DATA

MEMBRANE MATERIAL	FILLER FLUID 1,1,2,2 TETRABROMOETHANE/ETHYL ALCOHOL ($C_2H_2Br_4$)					FILLER FLUID LITHIUM IODIDE/WATER (LiI)					
	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (%)	Yield Stress (psi)	Yield Strain (%)	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (%)	Yield Stress (psi)	Yield Strain (%)	
MYLAR A	15,027	155	1,559			25,030	80	12,130	19,240	10	
RHENO #55	DELAMINATED					1,226	137	266			
ACLAR 22-C	1,682	600	1,303	1,933	12	1,989	456	1,839	2,484	14	
CELANAR 300 SERIES/2000	18,401	100	3,643			28,835	94	5,078	16,666	7	
CAPRAN 77C	7,059	226	4,267			DISSOLVED					
VELOSTAT	1,279	24	223			DELAMENATED					
H-FILM	20,812	130	5,470			17,160	26	7,867			
COST OF FILLER FLUIDS (COST/LB OF SOLUTION)	$5.95					$2.60					
COMPOSITION & SPECIFIC GRAVITY OF FILLER FLUIDS	74.07% $C_2H_2Br_4$ 25.93% C_2H_5OH 1.779 gm/cc @26°C					56.00% LiI 44.00% Water 1.684 gm/cc @18°C					

TABLE V

MEMBRANE - FILLER FLUID EVALUATION DATA

MEMBRANE MATERIAL	FILLER FLUID CLAY/WATER					TEAR STRENGTH		BURST STRENGTH	PERMEABILITY	COST OF MEMBRANE MATERIALS (Cost/sq. ft.)
	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (psi)	Yield Stress (psi)	Yield Strain (%)	Initial (Graves) (grams/mil)	Propagated (Elmendorf) (grams/mil)	(Mullen) (psi)	Water Vapor Trans. Rate [gm/100 in^2/24 hrs./mil]	
MYLAR A	25,400	150	15,417	19,500	13	(1 mil) 600 1300 lbs/in	15 (1 mil)	66 (1 mil)	1.8 (1 mil)	$0.076 (7.5 mil)
RHINO #55	2,293	346	774			After tear starts exceeds 100 lbs., 1" tear started using tensile machine pulling at corners 1 sq. yd. material		85 (7 mil)	.05 grains/hr./ 100 sq. in.	$0.050 (7 mil)
ACLAR 22-C	4,998	11	4,141	3,624	38	370 (1 mil) 2300 (5 mil)	12 (1 mil)	23 (1 mil) 66 (5 mil)	0.045 (1 mil) 0.028 (2 mil)	$0.507 (7.5 mil)
CELANAR 300 SERIES/2000	27,264	146	14,921	17,490	11	2.5 lbs. (1 mil)	27 (1 mil)	80 (1 mil)	1.7 (1 mil)	$0.078[c] (7 mil)
CAPRAN 77C	6,333	344	3,087			500-600 (1 mil)	50-90 (1 mil)	Does Not Burst 16-18 (1 mil)	19-20 (100°F, 90% R.H.) (1 mil)	$0.056 (5 mil)
VELOSTAT	DELAMINATED					DATA NOT AVAILABLE				$0.540 (20 mil)
H-FILM	NOT TESTED					800 (1.5 mil)	20 (1.5 mil)	75 (1.5 mil)	0.8 (1.5 mil)	$0.926[d] (5 mil)
COST OF FILLER FLUIDS (COST/LB OF SOLUTION)	$0.00116[a]									
COMPOSITION & SPECIFIC GRAVITY OF FILLER FLUIDS	70% Clay 30% Water 1.750 gm/cc @ 26.8°C									

c. Estimated price based on 5 mil values. Thickness of 7 mils will be available in late 1966 or early 1967.

d. H-film currently available in film thickness through 5 mils only

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TABLE VI

PROPELLANT - MEMBRANE COMPATIBILITY TEST RESULTS

Membrane Material	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (psi)	Yield Stress (psi)	Yield Strain (psi)
	(28,420)	(102)			
H-Film	21,485	102	6454	--	--
	(27,146)	(151)			
Celanar	17,095	27	9190	--	--
	(26,066)	(152)			
Mylar	15,292	112	4417	10,792	10
	(5,165)	(17)			
Aclar	1,990	465	1276	2,352	18

(Average of 3 tests @ 145°F)

NOTE: One side of film was in contact with TP-H8163 propellant for 162 hours @ 145°F. Two specimens of each film were left in contact with the propellant for a total of 22 days to observe the effect of aging. Results are below.

Membrane Material	Ult. Stress (psi)	Ult. Strain (%)	Stress @ 5% Strain (psi)	Yield Stress (psi)	Yield Strain (psi)
	(28,420)	(102)			
H-Film	21,410	99	5046	--	--
	(27,146)	(151)			
Celanar	22,100	51	12036	14,533	7
	(26,066)	(152)			
Mylar	23,000	109	15334	15,333	6
	(5,165)	(17)			
Aclar	2,142	123	1993	2,622	11

(Average of 2 tests @ 145°F)

NOTE: Values shown in parentheses are for membrane material which had not been exposed to propellant.

TABLE VII

PERMEABILITY TESTS OF MEMBRANE MATERIALS

MEMBRANE/FILLER FLUID	PERMEABILITY (grams/100 in^2/24 hrs/2 mils)
Mylar/Clay-Water	
Avg. over 28 day period -	7.963
Avg. over 13 day period -	10.73
Avg. over 6 day period -	10.60
Mylar/$ZnCl_2$	
Avg. over 11 day period -	0.9177
Avg. over 6 day period -	0.8235
Mylar/$ZnBr_2$	
Avg. over 13 day period -	3.8182
Avg. over 6 day period -	4.2864
Celanar/Clay-Water	
Avg. over 11 day period -	2.3118
Avg. over 5 day period	2.2812
Celanar/$ZnCl_2$	
Avg. over 11 day period -	0.7365
Avg. over 5 day period -	0.8721
Celanar/$ZnBr_2$	
Avg. over 11 day period -	1.5273
Avg. over 5 day period -	1.6775

NOTE: Tests conducted at 145°F.

TABLE VIII

PEEL TESTS

MEMBRANE MATERIALS TO TP-H8163 PROPELLANT

Membrane Material	Peel Lbs/Linear Inch	Comments
Tests run at 77°F:		
MYLAR	1.25	Thin coat of propellant left on film
H-Film	1.20	Thin coat of propellant left on film
Celanar	1.30	Thin coat of propellant left on film
Aclar	0.25	Film surface clean
Tests run at 145°F:		
MYLAR	0.55	Thin coat of propellant left on film
H-Film	0.50	Thin coat of propellant left on film
Celanar	0.55	Thin coat of propellant left on film
Aclar	0.20	Film surface clean

NOTE: All membranes in contact with propellant for 5 days at 145°F (cure cycle) prior to test

TABLE IX

ADHESIVE BONDING OF VARIOUS FILMS AFTER AGING TWO WEEKS AT 77°F

Adhesive	ACLAR	H-Film	MYLAR	CAPRAN
DC 92-018	Peels easily. Good bond.	Good.	Good.	Ex. St. of F.
NS-366 267	N. B.	N. B.	Fair.	Ex. St. of F.
NS-366 327	Fair.	Fair.	N. B.	Ex. St. of F.
PPG-529	N. B.	N. B.	N. B.	N. B.
PPG-218-34	Good.	Fair.	Good.	Ex. St. of F.
PPG-431	N. B.	N. B.	N. B.	N. B.
E-910	N. B.	Excellent.	Ex. St. of F.	Ex. St. of F.
Boxer Epoxy	Excellent.	Excellent.	Ex. St. of F.	Ex. St. of F.

D C = Dow Corning
N S = National Starch & Chemical Corporation, New York, N. Y.
PPG = Pittsburg Plate Glass Co., Adhesive Product Division, Bloomfield, N.J.
Boxer Epoxy = Union Laboratories, Inc., Morganville, N. J.
N. B. = No bond.
Ex. St. of F. = Exceeds strength of film.

TABLE X

SPECIFIC GRAVITY OF HEAVY ORGANIC LIQUIDS

Liquid	Specific Gravity
Tribromomethane (Bromoform)	2.890
Dibromobenzene	1.956
Ethylene Dibromide (1, 2-Dibromoethane)	2.180
Ethylene Bromohydrin (Bromoethanol)	1.772
Ethyl Iodide	1.933
Iodobenzene	1.824
Methyl Iodide	2.279
Propylene Bromide (1, 2-Dibromopropane)	3.325
Methylene Iodide (Diiodomethane)	2.964
Acetylene Tetrabromide (Tetrabromoethane)	1.987

TABLE XI

SPECIFIC GRAVITY OF AQUEOUS SOLUTIONS OF INORGANIC SALTS

Salt	Weight, %	Temperatures	Specific Gravity
Silver Fluoride	60	18/4°C	2.26
Silver Nitrate	70	20/4°C	2.33
Barium Iodide	60	20/4°C	1.97
Cesium Chloride	60	20/4°C	1.79
Ferric Sulfate	60	17.5/4°C	1.80
Selenic Acid	80	20/4°C	2.12
Lithium Iodide	60	20/4°C	1.78
Rubidium Iodide	60	20/4°C	1.81
Stannous Chloride	60	15/4°C	1.77
Stannic Chloride	70	15/4°C	1.97
Zinc Bromide	60	20/4°C	1.87
Zinc Chloride	70	20/4°C	1.96
Zinc Iodide	70	20/4°C	2.20

TABLE XII

HAZARD DATA ON HEAVY ORGANIC LIQUIDS

LIQUID	TOXICITY	VAPOR PRESSURE	THRESHOLD LIMITS		TOXIC HAZARD RATING *											
					ACUTE						CHRONIC					
					LOCAL			SYSTEMIC			LOCAL			SYSTEMIC		
			ppm in air	milligrams per cubic meter of air	Irritant	Ingestion	Inhalation	Ingestion	Inhalation	Skin Absorption	Irritant	Ingestion	Inhalation	Ingestion	Inhalation	Skin Absorption
Tribromomethane (Bromoform)	Causes lachrymation. Can damage liver seriously or cause death. Anesthetic properties similar to chloroform narcotic effects.	---	---	---	-	2	2	2	2	-	2	-	-	2	2	-
Dibromobenzene	Details unknown. A fumigant. Limited toxicity with animals. Emits toxic bromides when decomposes.	1 mm at 60°C	---	---	-	-	-	-	-	-	-	-	-	-	-	-
Ethylene Dibromide (1, 2-Dibromoethane)	Irritating to eyes, nose and throat, followed by dissiness, nausea, vomiting and loss of consciousness. Strong local irritating effects. Irritation of eyes and upper respiratory passages. Strong narcotic action.	17.4 mm at 30°C	25	190	3	3	3	3	3	3	2	-	-	2	2	2
Ethylene Bromohydrin (Bromoethanol)	---	---	---	---	-	-	-	-	-	-	-	-	-	-	-	-
Ethyl Iodide	Narcotic in high concentrations. Produces toxic and corrosive fumes when in contact with water.	100 mm at 15°C	---	---	U	U	U	-	2	-	1	-	-	-	2	2
Iodobenzene	---	---	---	---	-	-	-	-	-	-	-	-	-	-	-	-
Methyl Iodide	Strong narcotic and anesthetic. Emits highly toxic iodides when it decomposes.	400 mm at 25.3°C	---	---	2	2	2	3	3	3	U	U	U	2	2	2
Propylene Bromide (1, 2-Dubromopropane)	Highly toxic	---	---	---	-	-	-	-	-	-	-	-	-	-	-	-
Methylene Iodide (Diiodomethane)	Emits toxic fumes when it decomposes															
Acetylene Tetrabromide (Tetrabromoethane)	When heated, emits highly toxic carbonyl bromide.	---	1	14	2	2	2	U	U	U	U	U	U	U	U	U

* Toxic Hazard Rating:
- O No harm under any condition
- 1 Slight. Causes readily reversible changes which disappear at end of exposure
- 2 Moderate. May involve reversible or irreversible changes. Won't cause death or permanent injury.
- 3 High. May cause death or permanent injury after very short exposure to small quantities
- U Unknown. No information on humans considered valid.

TABLE XIII

HAZARD DATA ON SOLVENTS FOR HEAVY ORGANIC LIQUIDS

Solvent	Vapor Pressure	Threshold Limits
Carbon Tetrachloride	100 mm at 74°F	10 ppm in air 65 milligrams/m^3 of air

Hazards

Can be absorbed via intact with skin. Has narcotic action similar to chloroform. After long exposure at high concentrations, workers may become unconscious and, if exposure continues, death may follow from respiratory failure. Exposure to lower concentrations produce severe intestinal upset and may progress to serious kidney and hepatic damage. There is usually no permanent injury to such exposure. Variable susceptibility in different people. Prolonged exposure to small amounts has been reported to have caused cirrhosis of the liver. May produce dermatitis after extended exposure to liquid. Irritating to eyes.

Ethyl Alcohol	40 mm at 67°F	1000 ppm in air 1880 milligrams/m^3 of air

Hazards

No cumulative effects as it is rapidly oxidized in the body. Some irritant action on the mucous membranes of the eyes and upper respiratory tract. Can react vigorously with oxidizing materials. Dangerous when exposed to flame.

Methyl Alcohol	100 mm at 74°F	200 ppm in air 262 milligrams/m^3 of air

Hazards

possesses narcotic properties. Slight irritant to mucous membranes. Affects nervous system, particularly optic nerves and possibly the retinae. Once absorbed, it is very slowly eliminated. In body, it is oxidized to other toxic materials. Regarded as a cumulative poison. Severe exposure may cause dizziness, unconsciousness, sighing respiration, cardiac depression and eventually death. With less severe exposure, blurring of vision occurs. May progress to actual blindness. Can react vigorously with oxidizing materials.

TABLE XIII(Continued)
HAZARD DATA ON SOLVENTS FOR HEAVY ORGANIC LIQUIDS

Solvent	Vapor Pressure	Threshold Limits
Ethyl Ether	442 mm at 65°F	400 ppm in air 1212 milligrans/m^3 of air

Hazards

Not corrosive or dangerously reactive. Not considered safe to inhale or ingest. It is a depressant of the central nervous system and can produce drowsiness, stupor and uncounsciousness. Severe and continuous exposure may cause death due to respiratory failure. Can react vigorously with oxidizing materials. Highly dangerous in the presence of flame.

TABLE XIV

HAZARDS DATA ON INORGANIC SALTS

Salt	Threshold Limits
Silver Fluoride	2.5 milligrams/m^3 of air

Hazards

Highly irritant and toxic. Acute effects are the results of hydrofluoric acid. Chronic poisoning consists of sclerosis of bones caused by fixation of calcium by fluorine. Effects are loss in weight, anemia and teeth defects. Absorption into circulation system and subsequent deposition on body tissues may cause greyish pigmentation of skin and mucous membranes.

Silver Nitrate -----

Hazards

Powerful caustic. Absorption into circulation system and subsequent deposition on body tissues may cause greyish pigmentation of skin and mucous membranes. Large amounts taken orally may have serious or fatal results.

Barium Iodide 0.5 milligrams/m^3 of air

Hazards

Poisonous when taken orally.

Cesium Chloride -----

Hazards

Very minor tocicity.

Ferric Sulfate -----

Hazards

Practically non-toxic. May cause local irritation.

Lithium Iodide -----

Hazards

Prolonged absorption may cause skin rash, headaches and irritation of mucous membranes. In severe cases skin may show redness and blisters. Weakness, anemia, loss in weight and general depression may occur.

TABLE XV

COMPATIBILITY OF CANDIDATE FILLER FLUIDS WITH METALS

Type Metal	Filler Fluid	% Weight Loss or Gain	Remarks
303 S. S.	$ZnBr_2$	- .039	No visual change
303 S. S.	$ZnCl_2$	- .190	Metal had a dull cast
303 S. S.	Clay/Water	- .048	No visual change
4133 Steel	$ZnBr_2$	-1.470	Metal turned dark, fluid rusty color
4133 Steel	$ZnCl_2$	- .230	Metal assumed a rust color
4133 Steel	Clay/Water	- .139	Metal burned black
6061 T-6 Aluminum	$ZnBr_2$	- .986	Evidence of reaction - discoloration
6061 T-6 Aluminum	$ZnCl_2$	+3.390	Heavy white coating - probably hydrated aluminum
6061 T-6 Aluminum	Clay Slurry	+ .042	No evidence of reaction - beige tint on aluminum

NOTE: Immersed in solutions for 7 days @ 145°F.

TABLE XVI

UNDESIRABLE CHARACTERISTICS OF RESIN SYSTEMS STUDIED

Resin System	Undesirable Characteristics
Polyethylene	Low melting point; limited solubility; high shrinkage.
Polypropylene	Limited solubility; high shrinkage.
Polyvinyl chloride	Self-extinguishing.
Polystyrene	Picks up electrostatic charge easily.
Acrylics	Pronounced delay pseudoelastic effects; may require annealing.
Polyvinylidene chloride	Pure polymer is hard crystalline material.
Acrylonitrile	Produces electrostatic charge easily; required orientation to maximize properties.
Polytetrafluoroethylene	Working temperatures above 620°F.
Polychlorotrifluoroethylene	Working temperatures too high.
Cellulose nitrate	Instable at molding temperature; shrinkage due to solvent fabrication.
Phenolic plastics	Require high laminating pressures; form water during curing; require high oxidizer content to burn.
Furfural resins	Require high laminating pressures; form water during curing; require high oxidizer content to burn.
Amino plastics	High shrinkage during curing; many do not carbonize easily.
Polyamides	High melt temperature; low solubility; high shrinkage.
Silicones	High cost.

TABLE XVII

SAMPLES SUPPLIED TO THIOKOL

Sample Number	Formulation	Weight, %
16283-4A (Laminated at 100°C and 200 psi)	Resin (VYHD)	24.0
	Cotton Gauze	19.9
	Ammonium Perchlorate (NH_4ClO_4)	56.1
16283-4A1 (Laminated at 100°C and 200 psi)	Resin (VYHD)	24.2
	Cotton Gauze	18.0
	Ammonium Perchlorate	57.8
16283-8B (Laminated at 100°C and 200 psi	Resin (VYHD)	22.2
	Cotton Gauze	26.0
	Ammonium Perchlorate	51.8
16283-15-10	Resin, Epon-1001 + 2% BF_3-400	25.9
	Cotton Gauze	14.1
	Ammonium Perchlorate	60.0
16283-15-20	Resin, Epon-1001 + 2% BF_3-400	25.9
	Cotton Gauze	14.1
	Ammonium Perchlorate	60.0
16283-15-30	Resin, Epon-1001 + 2% BF_3-400	25.9
	Cotton Gauze	14.1
	Ammonium Perchlorate	60.0
16283-18-10	Resin, Epoxide 2774: HB Polymer, 1:1	27.5
	Cotton Gauze	11.8
	Ammonium Perchlorate	60.7

TABLE XVIII

FORMULATIONS REPORTED BY IITRI BUT NOT SUPPLIED TO THIOKOL

Sample Number	Formulation	Weight, %
16283-12C (Laminated at 135°C)	Resin, Epon-1001/BF_3-400	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16283-12B (Laminated at 135°C)	Resin, Epon-1001/BF_3-400	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16283-12A (Laminated at 135°C)	Resin, Epon-1001/BF_3-400	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16283-16 (Laminated at 110°C)	Resin, Epon-1001/BF_3-400	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16283-21-3S (Laminated at 135°C)	Resin, Epon-828/Epon-1001 + BF_3-400	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16283-21-8L (Laminated at 135°C)	Resin, Epon-828/Epon-1001	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16283-21-12L (Laminated at 115°C)	Resin, Epon-828/Epon-1001	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16283-21-16L (Laminated at 115°C)	Resin, Epon-828/Epon-1001	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16283-22-1L (Laminated at 115°C)	Resin, Epon-828/Epon-1001	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16283-22-6L (Laminated at 115°C)	Resin, Epon-828/Epon-1001	26 - 27
	Cotton Gauze	12 - 13
	Ammonium Perchlorate	61
16273-7A	Resin	Unknown
	Cotton Gauze	Unknown
	Ammonium Perchlorate	Unknown

TABLE XIX

STRESS STRAIN DATA

(IITRI)

Sample No.	Resin System	Lamination Pressure (psi)	Average Data: Tensile Strength (lb/in^2)	Average Data: Elongation (%)	Average Data: Mean Rate of Stressing (lb/in^2-sec)
16283-15-10	Epon/BF_3	10	2572	2.45	72
16283-15-20	Epon/BF_3	20	4326	1.93	113
16283-15-30	Epon/BF_3	30	4342	1.59	116
16283-18	Epoxide/HB	10	3121	4.50	61
*	VYHD	200	5250	6.82	101

*25.07 wt % VYHD, 16.4% cotton gauze, 58.45 wt % A.P.

TABLE XX

AVERAGE MEASURED TENSILE PARAMETERS AS FUNCTIONS OF COMPOSITION AND PROCESSING VARIABLES[a]

(IITRI)

AP (%)	Resin (%)	Lamination Pressure (psi)	Stensile Strength (psi)	Elongation (%)	Density (g/cc)
58	29	10	3300	1.25	1.33
		20	4000	1.25	1.45
		30	5000	1.25	1.55
61	26	20	2900	1.80	1.35
		30	3400	1.60	1.45
65	23	20	2600	1.45	1.35
		30	3200	1.25	1.46

[a]Cure temperature 135°C for 16 hours

TABLE XXI

STRESS-STRAIN AND MODULUS DATA*

Sample No.	Resin System	Ult. Stress (psi)	Ult. Strain (%)	Modulus (psi)
16283-B	VYHD	5297	5.8	-----
16283-4A	VYHD	5602	8.7	-----
16283-15-10	Epon/BF_3	2486	1.9	254,484
16283-15-20	Epon/BF_3	4225	2.65	293,771
16283-15-30	Epon/BF_3	3251	1.824	316,928
16283-18-10	Epoxide/HB Polymer	3571	6.61	207,594

Test Temperature 77°F

*Thiokol Data

TABLE XXII

PROPERTIES OF EPOXIDE LAMINATES WITH VARIOUS AMMONIUM PERCHLORATE CONTENTS*

AP (%)	Modulus of Elasticity (psi)	Ultimate Strain (%)	r_b (in/sec)	Density (g/cc)
58	467,000	1.5	5	1.48
61	362,000	1.5	5	1.47
65	366,000	1.5	5	1.56

* Data obtained from IITRI in Thiokol-IITRI Meeting, 8 February 1966

TABLE XXIII

TENSILE PROPERTIES OF EPOXIDE LAMINATES WITH VARIOUS HB POLYMER LEVELS*

Type Epoxy	Binder Distribution		AP (%)	Modulus of Elasticity	Extensibility (%)	Tensile Strength (psi)
	Epoxy (%)	HB Polymer (%)				
2774	50	50	64	198,000	4.00	3120
1001	60	40	64	307,000	2.18	3250
1001	70	30	64	322,000	1.50	2400
1001	100	0	64	366,000	1.25	3500
1001	40	60	64	200,000**	4.00**	2500**

* Data obtained from IITRI in Thiokol-IITRI Meeting 8 February 1966
** Estimated values - subject to verification by testing

TABLE XXIV

AVERAGE MEASURED PHYSICAL PROPERTIES
AS A FUNCTION OF COMPOSITION AND PROCESSING VARIABLES

AP (%)	Resin (%)	Lamination Pressure (psi)	Tensile Strength (psi)	Elongation (%)	Bulk Density (g/cc)
58.1	29.0	10	3300	1.25	1.33
		20	4000	1.25	1.45
		30	5000	1.25	1.55
61.0	26.2	20	2900	1.80	1.35
		30	3400	1.60	1.45
64.7	23.0	20	2600	1.45	1.35
		30	3200	1.25	1.46

TABLE XXV

PHYSICAL PROPERTIES OF COMBUSTIBLE CORE MATERIAL

Cure Time (hr.)	Density (g/cc)	Temperature (°F)	Tensile Strength (psi)	Elongation (%)	Modulus of Elasticity (psi)
20	1.489	77	3200	2.9	221,000
		145	2645	3.2	370,000
40	1.441	77	1900	1.4	224,000
		145	1500	1.5	136,000
60	1.409	77	1900	1.7	196,000
		145	1700	2.2	134,000
		195	1000	3.8	68,000

TABLE XXVI

DENSITIES FOR VARIOUS COMPOSITIONS AND FABRICATION PARAMETERS

Sample No.	Resin System	A. P. Weight (%)	Laminating Temperature (°C)	Laminating Pressure (psi)	Density (g/cc)
16283-4A	VYHD	56.1	100	200	1.4236*
16283-8B	VYHD	51.8	100	200	1.2658*
16283-21-8L	Epon 828/1001	61	135	30	1.39
16283-21-12L	"	61	115	20	1.36
16283-21-16L	"	61	115	30	1.43
16283-22-1L	"	65	115	20	1.34
16283-22-6L	"	65	115	30	1.43
16283-22-9L	"	65	135	20	1.40
16283-22-13L	"	65	135	30	1.45
16283-23-2L	"	58	135	20	1.57
16283-23-6L	"	58	135	10	1.39
16283-23-10L	"	58	115	20	1.48
16283-23-14L	"	58	115	30	1.55
16283-22-1	"	65	RT	40	1.10
16283-22-2	"	65	RT	80	1.19
16283-22-3	"	65	RT	150	1.25
16283-22-4	"	65	RT	267	1.33
16283-22-5	"	65	RT	300	1.31
16283-22-6	"	65	RT	600	1.38

*Tested by Thiokol - All other samples tested by IITRI

Note: IITRI values obtained from Mr. Abel, IITRI by telephone, 17 February 1966

TABLE XXVII

FORMULATIONS, DENSITIES, AND POROSITIES OF COMBUSTIBLE CORES SENT TO THIOKOL FOR IGNITION TESTING AND MOTOR LOADING

Sample No.	AP (%)	Gauze (%)	Epon-1001 (%)	HB Polymer (%)	Density (g/cc)	Porosity (% Voids)
16747-12-I[a]	56.05	12.42	17.34	14.19	1.263	21.7
16747-12-II[a]	56.05	12.42	17.34	14.19	1.259	21.9
16747-12-III[a]	56.05	12.42	17.34	14.19	1.267	21.5
16747-12-IV[a]	56.05	12.42	17.34	14.19	1.286	20.3
16747-13-5[b]	56.26	12.13	17.40	14.24	1.399	13.3
16747-15-6[b]	56.12	12.30	17.36	14.21	1.448	10.2
16747-17-7[b]	55.65	13.04	17.22	14.08	1.454	9.9
16747-17-8[b]	55.65	13.04	17.22	14.08	1.400	13.2
16747-21-1[c]	56.03	12.45	17.33	14.18	1.389	13.9
16747-21-2[c]	56.03	12.45	17.33	14.18	1.398	13.3
16747-21-3[c]	56.03	12.45	17.33	14.18	1.354	16.1
16747-21-4[c]	56.03	12.45	17.33	14.18	1.397	13.4
16747-21-5[c]	56.03	12.45	17.33	14.18	1.345	16.6
16747-21-6[d]	56.03	12.45	17.33	14.18	1.312	18.7

a. Core with 7/8-inch wall; sectioned into 3-inch lengths for ignition testing.
b. Core with 7/8-inch wall; sectioned into 11.88-inch lengths for ignition testing.
c. Core with 1/8-inch wall for motor loading.
d. Block with 1-inch thickness for physical testing.

TABLE XXVIII

REACTION TEMPERATURES OF COMBUSTIBLE CORE MATERIALS

Compound	Temperature (°C)	Point	Remarks
AP	244	Endotherm	
	366	Exotherm	
Cotton Gauze	237	Exotherm	Slight
Epon-101/Epon 828 2% BF_3-400	168	Exotherm	Slight, ends at 400°C
Core Material I[a]	233	Exotherm	Slight
	243	Endotherm	
	280	Exotherm	Strong
Core Material II[b]	191	Exotherm	Slight
	243	Endotherm	
	254	Exotherm	Strong
Core Material III[c]	209	Exotherm	Slight
	243	Endotherm	
	286	Exotherm	Strong

a. 12.3% gauze, 64.7% AP, and 23.0% resin (Epon-1091/Epon-828 2% BF_3-400).
b. 11.7% gauze, 60.74% AP, and 27.0% resin (50% Epoxide 2774, 50% HB polymer).
c. 16.4% gauze, 58.45 AP, and 25.0% resin (VYHD).

TABLE XXIX

AUTOIGNITION TEMPERATURE OF COMBUSTIBLE CORE MATERIAL

Sample Number	Oven Temperature (°F)	Total Exposure Time		Exotherm (°F) To:	Results
		Hours	Minutes		
1	400	2	2.5		NF
2	530		1.5		F
3	500		4		F
4	475		7		F
5	440	1	30	450 after 7 minutes	NF
6	450	1	12	460 after 5 minutes	NF
7	460		5.5	470 after 2-1/2 minutes	F
8	460	1	40	470 after 7 minutes	NF
9	470		6		F
10	465		45	475 after 7 minutes	NF
11	470		6		F
12	465		7	485 after 5 minutes	F
13	465		30	470 after 7 minutes	NF

NOTES:

Sample size - 0.5 gram
Tested in forced convection oven
F - fired
NF - no fire

TABLE XXX

COMPARISON OF IITRI AND THIOKOL BURNING RATE VALUES

Sample No.	AP Content	Burning Rate (in/sec) Thiokol		IITRI
16283-4A	57.8%	.516	±.050	.490
16283-8B	51.8%	.381	±.065	.582

Average of 4 samples
tested at 800 psi and 70°F

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TABLE XXXI

BURNING RATES FOR COMBUSTIBLE CORE FABRICATION AND COMPOSITIONAL VARIATIONS

Resin System	Sample No.	AP (%)	Laminating Temperature (°C)	Laminating Pressure (psi)	Burning Rate[a] (in/sec)	Coefficient of Variation (%)
Epon-1001/BF_3-400	16283-12C	61.0	135	10	54.800	25.8
	16283-12B	61.0	135	20	2.070	42.5
	16283-12A	61.0	135	30	0.820	4.9
	16283-15	60.0	135	10	67.400	12.0
	16283-15	60.0	135	20	1.160	20.0
	16283-15	60.0	135	30	1.560	26.8
	16283-16	61.0	110	30	2.230	63.7
HB Polymer + Epoxide 2774	16283-18	61.0	120	10	1.890	19.7
Epon-828/Epon-1001/BF_3-400	16283-21-3S	61.0	135	20	6.630	11.3
Epon-828/Epon-1001	16283-21-8L	61.0	135	30	2.680	18.0
	16283-21-12L	61.0	115	20	53.800	6.8
	16283-21-16L	61.0	115	30	32.400	13.4
	16283-22-1L	65.0	115	20	35.400	16.6
	16283-22-6L	65.0	115	30	19.000	12.5
	16283-22-9L	65.0	135	20	36.100	28.7
	16283-22-13L	65.0	135	30	1.070	36.6
	16283-23-2L	58.0	135	20	0.805	13.6
	16283-23-6L	58.0	135	10	42.700	11.6
	16283-23-10L	58.0	115	20	4.220	45.1
	16283-23-14L	58.0	115	30	1.240	15.5
	16283-22-1	65.0	RT	40	87.000	18.7
	16283-22-2	65.0	RT	80	77.000	7.7
	16283-22-3	65.0	RT	150	71.500	7.8
	16283-22-4	65.0	RT	267	55.700	12.6
	16283-22-5	65.0	RT	300	62.600	8.4
	16283-22-6	65.0	RT	600	71.500	24.2

a. At 1,000 psi and 70°F.

TABLE XXXII

EFFECT OF DENSITY AND AP CONTENT ON BURNING RATE AT VARIOUS PRESSURES

Sample No.	Density (g/cc)	AP (%)	Burning Rate, in/sec Pressure, psi 1,000	500	300	200
16283-21-12L	1.32	61.0	53.80	36.10	21.400	--
16283-21-16L	1.39	61.0	32.40	13.20	--	0.284
16283-22-1L	1.10	65.0	35.40	20.00	11.300	--
16283-22-9L	1.39	65.0	1.25	1.19	0.435	--
16283-22-13L	1.45	65.0	1.05	0.64	0.430	0.320
16283-23-14L	1.56	58.0	1.25	0.60	0.370	0.220

TABLE XXXIII

BURNING RATES AT LOW PRESSURES (IITRI)

Sample No.	Burning Rate, (a) in/sec Pressure, psi 1,000	500	300	200
16283-21-12L	53.80	36.10	21.400	--
16283-21-16L	32.40	13.20	--	0.284
16283-22-1L	35.40	20.00	11.300	--
16283-22-9L	36.10	1.19	0.435	--

a= At 70°F

TABLE XXXIV

TRANSVERSE BURNING RATES

Sample No.	Density (g/cc)	AP (%)	Burning Rate, (a) in/sec Longitudinal	Transverse Method 1	Transverse Method 2
16283-23-6L	1.39	58.0	42.700	4.800	0.98
16283-23-2	1.57	58.0	0.805	0.560	--

a = At 1,000 psi and 70°F

TABLE XXXV

BALLISTIC CHARACTERISTICS OF COMBUSTIBLE CORE MATERIAL

Characteristic	Value (Propellant No.) 16283-23	16539-16
AP, wt. %	58.0	65.0
$_nRT$, lb_f-in/lb_m	1.035×10^6	2.9×10^6
I_{sp}, lb_f-sec/lb_m	122.5	206.0
C, ft/sec	2500	4190
C_F	1.58	1.58
V_E, ft/sec	3940	6630

TABLE XXXVI

SUMMARY OF COMBUSTIBLE CORE IGNITER AND MOTOR TESTS

Motor Designation	Motor Condition Live	Inert	Free Vol. (in^3)	Nozzle Throat Dia. (in)	Igniter Charge	Results
1		x	141	1.129	25 grams TICI	Normal igniter performance
2		x	141	1.071	25 grams TICI	Normal igniter performance
3	x		96	1.129	25 grams TICI	No Ignition - See Figure 45
3	x		96	1.071	25 grams TICI 10 grams TIC3 15 grams AlClO	Blew Up - See Figure 46
3A		x	86	1.071	Same as above	Normal igniter performance
4A		x	86	1.184	Same as above	Normal igniter performance
4B		x	86	1.184	25 grams TICI 14 grams TIC3 19 grams AlClO	Normal igniter performance
4	x		96	1.184	25 grams TICI 10 grams TIC3 15 grams AlClO	Hang-fire; motor burned after oscillograph turned off - See Figure 50
4		x	126	1.184	25 grams TICI 14 grams TIC3 19 grams AlClO	No material in motor to burn - igniter action only - See Figure 51

TABLE XXXVII

IITRI COMBUSTIBLE CORE MOTOR FIRINGS (SUMMARY)[1, 2, 3]

TX11 Motor No.	Core Wt. #	Core Density g/cc	Throat Size Area (sq. in)	Throat Size Dia. (in)	K_n Initial	K_n Final	IITRI Sample No.	P_{MAX} (psia)	Burning Time[4] (secs)	Remarks
3	1.380	1.263	1.0	1.129	25.9	42	16747-12 (I)			Did not ignite.
3	1.380	1.263	.9	1.071	24	46	16747-12 (I)	6000+	.034	Motor blew up (nozzle separation)
4	1.392	1.259	1.1	1.184	23.5	38	16747-12 (II)			Ignited. No discernable pressure contribution from combustible core.
5	1.457	1.399	1.0	1.129	25.9	42	16747-13-5			Ignited. No discernable pressure contribution from combustible core.
6	1.515	1.399	.9	1.071	24	46	16747-13-5			Ignited. Possible 10 psi over maximum igniter pressure.
7	1.43	1.446	.6475	.908	40	66.6	16747-15-6	500	.088	Chuffed;[5] clouds of black smoke covered test area.
8	1.41	1.446	.4316	.741	60	98.4	16747-15-6	870	.098	Chuffed; clouds of black smoke covered test area.
9	1.39	1.446	.3238	.624	80	131.0	16747-15-6	1090	.117	Chuffed; clouds of black smoke covered test area.
10	1.46	1.459	.259	.574	100	163.0	16747-17-7	4272+	.033	Blew up; nozzle separation. Igniter and plug had blown out.
11	1.52	1.459	.215	.523	120	197	16747-17-7	1283	.025	Ignited and burned; 3 or 4 chuffs.
12	1.44	1.459	.185	.485	140	229	16747-17-7	6976	.032	Blew up; nozzle separation.
13	1.54	1.40	.259	.574	100	163	16747-17-8	1200	.026	Ignited & burned; chuffed 10 or 12 times. Total time .128 sec.
14	1.54	1.40	.215	.523	120	197	16747-17-8	5666+	.059	Nozzle insert broke up. Chuffed 3 or 4 times.
15	1.54	1.40	.185	.485	140	229	16747-17-8			Was not fired; unable to remove igniter plug.

NOTES:
1. 6" long cases.
2. 2-3/4" I. D., 4-1/2 O.D., 3" long.
3. All tests were at ambient conditions.
4. This burning time is the time at which the pressure first returned to zero.
5. Chuffing is periodic burning after the pressure first returns to zero.

TABLE XXXVIII

CORE FORMING SYSTEM EVALUATION

Element Rating Weight		Comparison Element	RATING* Core Type: Collapsible	Membrane	Frangible	Combustible: Laminated	Castable
300	I.	Cost	75	129	300	76	191
		A. Mandrel					
		1. Material					
		a. Other than filler fluid					
		b. Filler Fluid					
		c. Reusable (i. e. for additional motors)					
		2. Fabrication					
		3. Transportation to Loading Plant - NOTE 1					
		4. Acceptance Inspection					
		B. Motor Processing Effects					
		1. Core check-out					
		2. Core preparation					
		3. Core installation					
		4. Clean and store					
		5. Between-use maintenance					
		6. Core removal					
		C. Special Tooling or accessories					
		1. Retracting platforms					
		2. Spindles					
		3. Transportation-Seals (Filler Fluid)					
		4. Transfer pumps or foam machines					
		5. Molds or presses (combustible and frangible)					
		6. Membrane tensioning device					
		7. Filler fluid storage tanks					
		8. Heat exchangers and fuel					
		9. Sensing devices					
		10. Trans. cost to use site					
300	II.	State-of-the-Art (at end of Phase I)	300	91	274	99	174
50		A. Present feasibility of concept	50	29	50	34	40
50		B. Degree of reduction to practice	50	11	45	18	17
100		C. Major problems to reduce to practice	100	0	89	20	57
100		D. Estimated Costs to solve C.	100	11	90	27	60
210	III.	Use	138	124	147	113	141
25		A. Safety	23	24	20	6	11
		1. Mandrel manufacture					
		2. Mandrel use (Motor processing - NOTE 2					
25		B. Design Latitude	6	5	25	13	25
40		C. Reliability	31	6	30	27	28
		1. Mandrel Manufacture					
		2. Formation of proper core configuration					
		3. Damage to grain - NOTE 3					
		4. Proper ignition					
		5. Removability					
30		D. Ballistic Effects	30	29	23	16	19
10		E. Vacuum casting	10	0	2	6	9
		1. Directly usable, not usable, modification required					
		2. Cost estimate if modification required					
30		F. Inspection	30	24	11	10	10
		1. Core itself	5	0	5	5	5
		2. Surveillance during casting	5	5	5	5	5
		3. Grain surface after cure	20	19	1	0	0
5		G. Grain design changes	3	5	4	4	4
25		H. Weights	11	11	21	19	21
		1. Total					
		2. Maximum unit to be handled					
		3. Additional in motor					
		a. During handling					
		b. During transportation to use site					
		c. During storage					
20		I. Cool-down	15	20	12	13	13
140	IV.	Motor Storage (Long or short-term)	80	96	96	91	91
60		A. Grain support	0	43	58	60	60
60		B. Compatibility of leave-in-place materials	60	33	39	31	31
20		C. Pre-launch inspection	20	20	0	0	0
90	V.	Launch Site Effects	50	51	33	39	46
25		A. Pad damage	25	24	13	16	21
		1. Combustible or frangible fragments					
		2. Leaking filler fluid					
25		B. Disposal or return of filler fluid	25	7	20	24	25
1000 1000			663	431	852	418	603

* Averages of seven estimates for II, III, IV, and V.

NOTES:
1. Either raw materials or completed core if manufactured out-of-house.
2. Will have to include core preparation, installation, casting, curing, core removal, or motor storage if left in place.
3. Susceptibility of core to damage before cure ends, leaking of filler fluid, etc.

TABLE XXXIX

COMPARISON OF MOTOR CHARACTERISTICS

	156" Space Booster Motor	110" TU-594 Motor
Throat diameter, in.	61.28	20.12
Throat area, $in.^2$	2940.	317.6
Port I.D., in.	116.	22.9
Grain O.D., in.	156.	108.
Web fraction	.257	.789
Port area, $in.^2$	5196.	411.8
Port to throat ratio	1.76	1.3
Web, in.	20	42.5

TABLE XL

CASTABLE COMBUSTIBLE CORE
FORMULATIONS AND PROPERTIES

(This table is classified Confidential and was intentionally omitted from the unclassified version of this report.)

TABLE XLI

COMPOSITION OF SELECTED FORMULATIONS

(This table is classified Confidential and was intentionally omitted from the unclassified version of this report.)

TABLE XLII

BALLISTIC DATA SUMMARY

TX-405 Motor Static Tests

Mix and Charge No.		Weight Burned (lbs)	K_n*	Web Burning Time (sec)	Chamber Press Av. (psi)	Characteristic Velocity C* (ft/sec)	Burning Rate (in/sec)	Grain Temp.	Air Temp. °F
12Q915	-1	0.32296	224	0.667	1036	3515	0.7496	Ambient	55
	-2	0.32296	168	0.646	808	3499	0.7740	Ambient	55
	-3	0.32252	280	0.670	1290	3487	0.7463	Ambient	55
	-4	0.32428	112	0.679	507	3485	0.7364	Ambient	55
12Q916	-1	0.3201	112	0.570	595	3505	0.8779	Ambient	57
	-2	0.3238	168	0.522	1015	3557	0.9578	Ambient	57
	-3	0.3230	224	0.540	1289	3597	0.9259	Ambient	57
	-4	0.3249	280	0.537	1642	3615	0.9310	Ambient	57
	-5	0.3219	335	0.546	1905	3483	0.9157	Ambient	57

* $K_n = \frac{A_s}{A_t}$

TABLE XLIII

CASTABLE COMBUSTIBLE CORE MATERIAL

EFFECT OF CURE CONDITIONS ON TENSILE PROPERTIES

Mix 12Q924

Duration (days)	1	3	6	10	14	1	3	6	10
Temperature (°F)	170	170	170	170	170	200	200	200	200
Tested at 77°F									
Modulus of Elasticity (psi)	6373	11698	10279	12988	14037	7851	12968	10519	15276
Strain at Cracking (%)	32.7	35.3	21.6	24.0	17.4	34.7	27.8	20.6	14.9
Strain at Max. Stress (%)	32.1	31.0	21.6	24.0	17.4	32.9	26.0	20.6	14.9
Stress (psi)	754	934	854	926	875	831	940	926	1005
Tested at 140°F									
Modulus of Elasticity (psi)	3306	4621	4458	4660	4427	3542	4478	4421	5623
Strain at Cracking (%)	13.6	15.1	16.4	12.2	12.2	12.8	17.0	14.8	10.5
Strain at Max. Stress (%)	13.6	15.1	16.4	12.2	12.2	12.8	17.0	14.8	10.5
Stress (psi)	316	366	413	346	356	326	401	421	397
77°F									
Compressive Modulus, psi		7143							

NOTE: All samples were subjected to 135°F for 24 hours prior to the above noted cure conditions.

TABLE XLIV

SHORT-TERM AGING - MIX NO. 120926

	A	B	C	D	E	F	G	H
-20°F								
Modulus, psi	84748							
Strain at Cracking, %	2.8							
Strain at Max. Stress, %	2.8							
Max. Stress, psi	2083							
0°F								
Modulus, psi	76915							
Strain at Cracking, %	3.2							
Strain at Max. Stress, %	3.2							
Max. Stress, psi	2194							
40°F								
Modulus, psi	42975							
Strain at Cracking, %	6.6							
Strain at Max. Stress, %	6.6							
Max. Stress, psi	1932							
77°F								
Modulus, psi	11024	11981	14513	10691	12026	10912	12611	13419
Strain at Cracking, %	25.6	27.2	23.1	23.3	22.0	26.5	30.2	20.5
Strain at Max. Stress, %	23.8	27.2	23.1	22.1	20.6	26.5	27.6	19.9
Max. Stress, psi	872	807	885	812	829	880	903	932
110°F								
Modulus, psi	4894							
Strain at Cracking, %	19.2							
Strain at Max. Stress, %	19.2							
Max. Stress, psi	441							
140°F								
Modulus, psi	4552	4421	5305	4143	4474	3914	4212	4372
Strain at Cracking, %	12.6	11.1	10.8	13.6	10.4	12.6	12.5	11.4
Strain at Max. Stress, %	12.6	11.1	10.8	13.6	10.4	12.6	12.5	11.4
Max. Stress, psi	370	340	351	370	347	357	360	363
Burn Rate, in/sec								
600 psi	0.58	0.59						0.58
1000 psi	0.56	0.59						0.58
1200 psi	0.57	0.56						0.54

Aging Conditions

No.	Aging Conditions
A	No aging
B	Ambient (1 week)
C	Ambient (2 weeks)
D	Ambient (1 month)
E	Ambient (1 week), 145°F (1 week), ambient (1 week)
F	Ambient (1 week), 145°F (1 week), ambient (2 weeks)
G	Ambient (1 week), 145°F (1 week), ambient (1 month)
H	Ambient (1 week), 145°F (1 week), 100°F (1 month)

TABLE XLV

DATA SUMMARY OF TX-11-37 MOTOR STATIC TESTS

(This table is classified Confidential and was intentionally omitted from the unclassified version of this report.)

TABLE XLVI

CONSUMABLE CORE IGNITION DATA FROM TX11-37 MOTOR TESTS

TX11-37 Mix & Charge	Ignition Time[a] (sec)	Pressure Rise Rate[b] (psia/sec)
B3132-1	0.035	18,567
B3132-2	0.035	20,385
B3132-3	0.030	31,176
B3132-4	0.040	26,500

a. Ignition Time is the time interval from fire command to 50 percent of maximum motor chamber pressure during ignition of the core.

b. Pressure Rise Rate is the average dP/dt between 100 psia chamber pressure and 90 percent of initial equilibrium pressure during ignition of the core.

TABLE XLVII

TX11-37 CASTABLE CONSUMABLE CORE
MOTOR TEST DATA AND
PREDICTED BALLISTIC PARAMETERS

TX11-37 Mix & Charge	Average Pressure (psia)	Burning Time (sec)	Characteristic Velocity[a] (ft/sec)	Burning[b] Rate (in/sec)
B-3132-1	876	0.410	--	0.813
B-3132-2	885	0.425	3961	0.792
B-3132-3	853	0.423	3903	0.796
B-3132-4	857	0.420	3977	0.773
Mean, $\overline{X}$	868	0.420	3947	0.794
Standard Deviation, S	15	0.006	39	0.016
Coefficient of Variation, CV, $\frac{S}{\overline{X}}$	0.0176	0.0151	0.0099	0.0203
Predicted	1160	0.410	3527	0.912

a. Characteristic Velocity = $\frac{g_c A_t \int Pdt_{total}}{w_f}$ (Values taken from motor data summary sheets)

b. Burning Rate = $\frac{r_{geometric} \int Pdt_{web}}{t_{50\%\text{-web}} \int Pdt_{total}}$

TABLE XLVIII

TRANSITION PHASE DATA FROM
TX11-37 MOTOR TESTS

TX11-37 Mix & Charge	Transition Duration (Zero Pressure) (sec)	Pressure Rise Rate[a] (psi/sec)
B-3132-1	1.010	13,978
B-3132-2	1.760	8,857
B-3132-3	2.700	3,267
B-3132-4	2.910	12,702

a. Pressure rise rate is the average dP/dt between 100 psia chamber pressure and 90 percent of initial equilibrium pressure during ignition of the propellant grain.

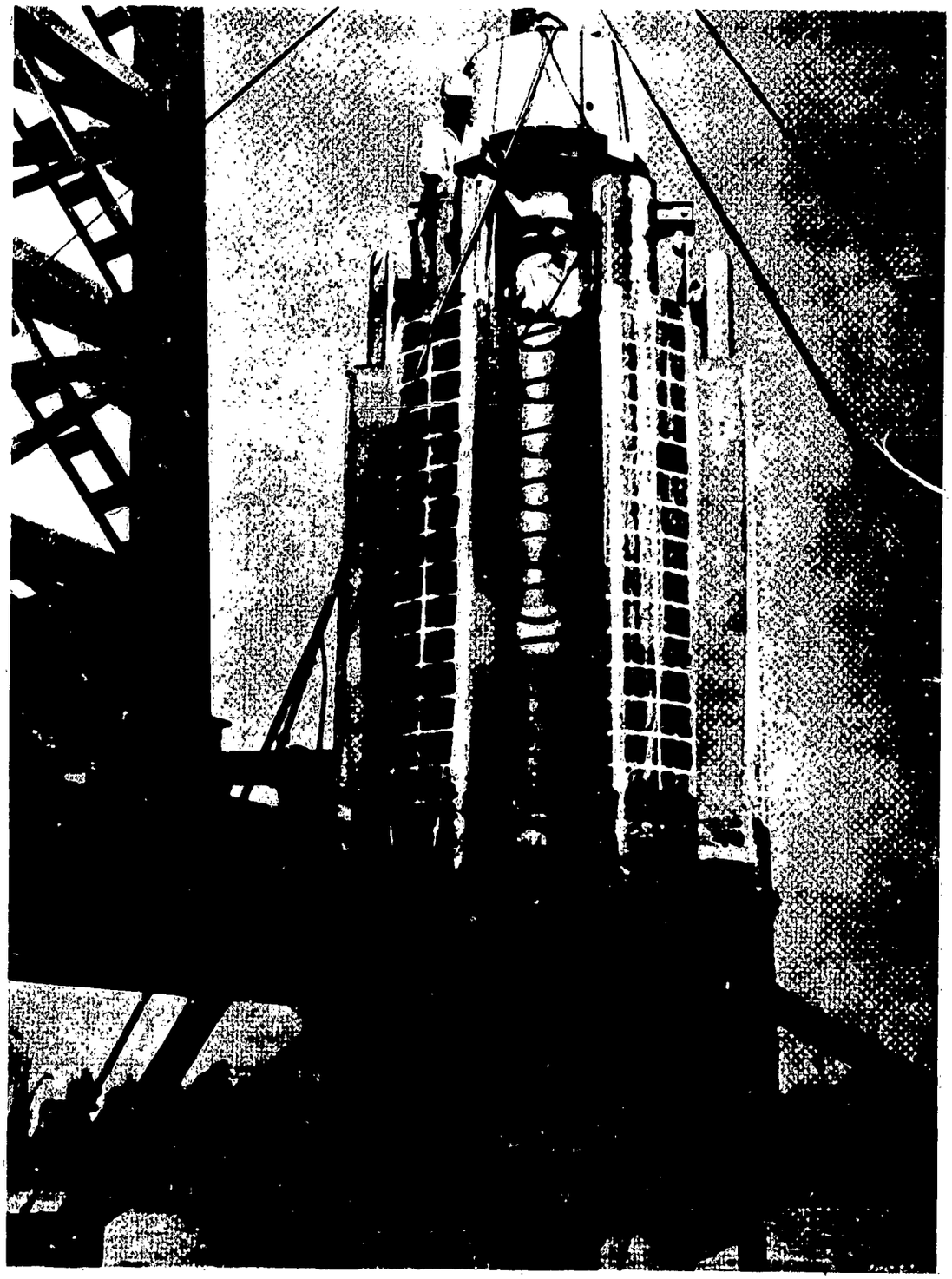


Figure 1. Photograph of Thiokol's Space Booster Collapsible Core.

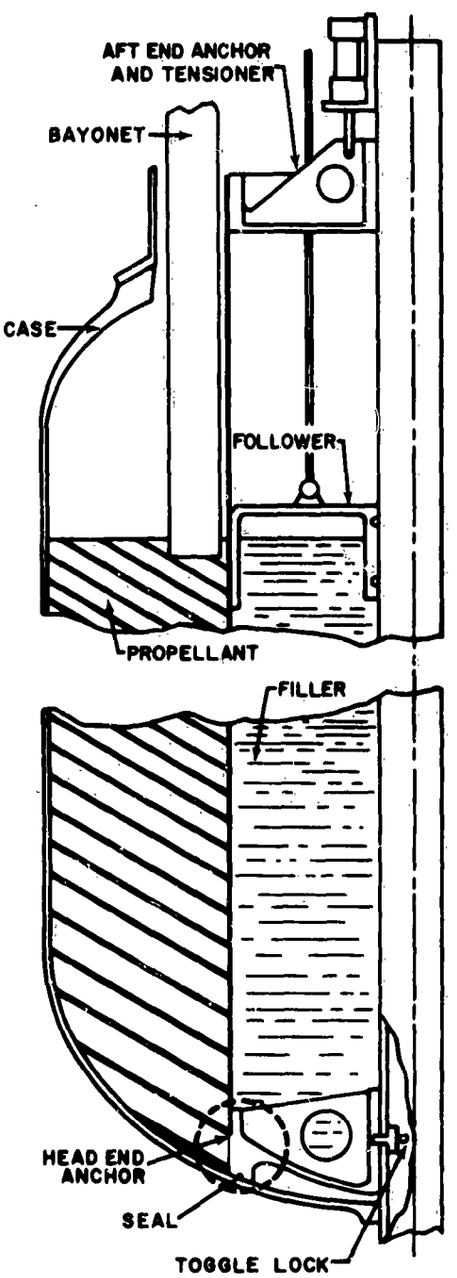


Figure 2. Sectional Schematic of Membrane Core

Figure 3. Photograph of Membrane Material Permeability Test Setup

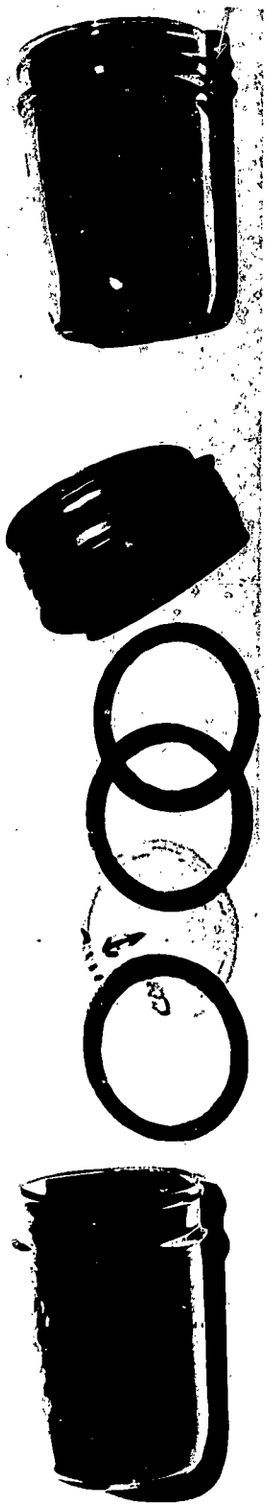


Figure 4. Photograph of Components of Permeability Test Apparatus

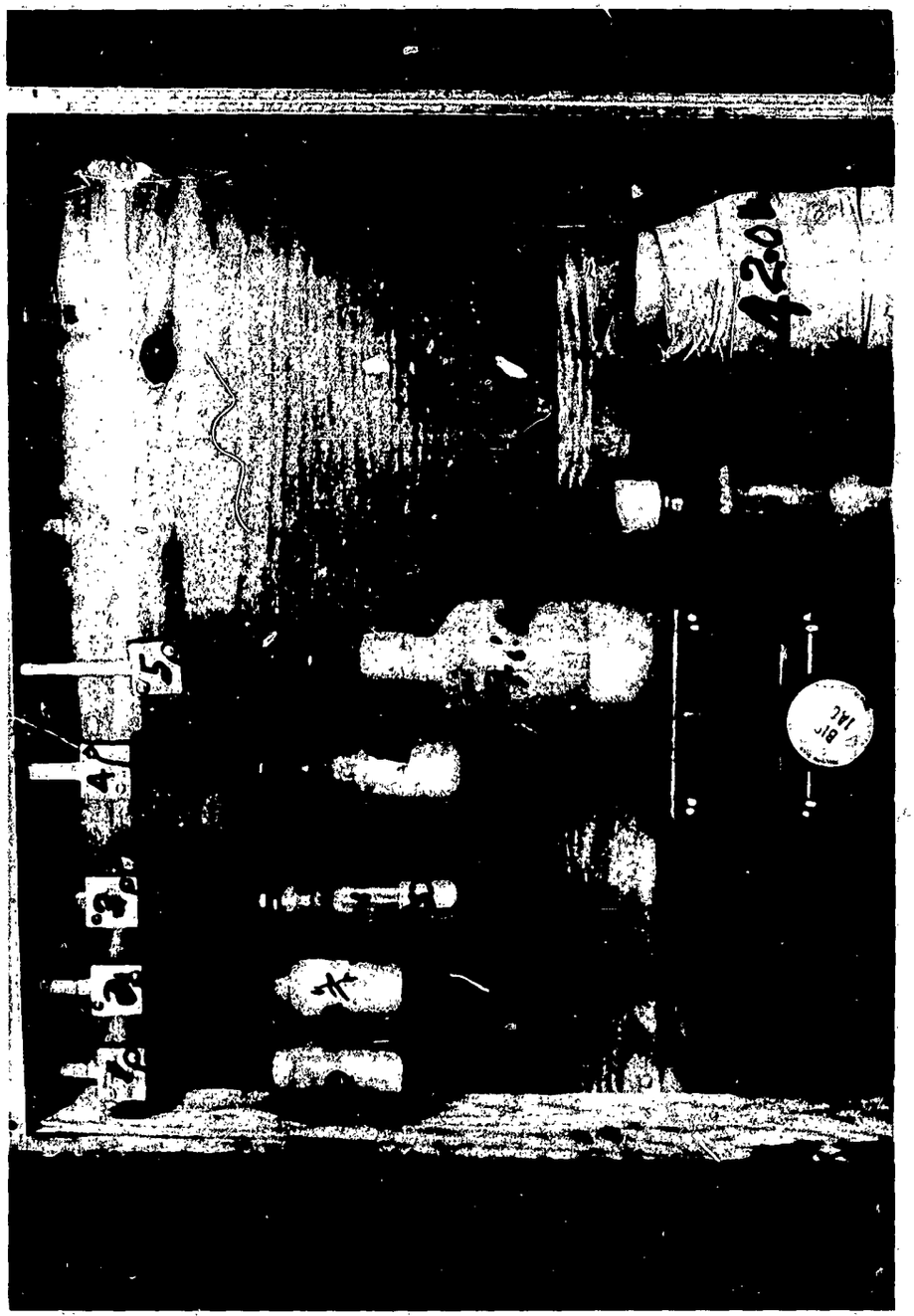


Figure 5. Photograph of Creep Test

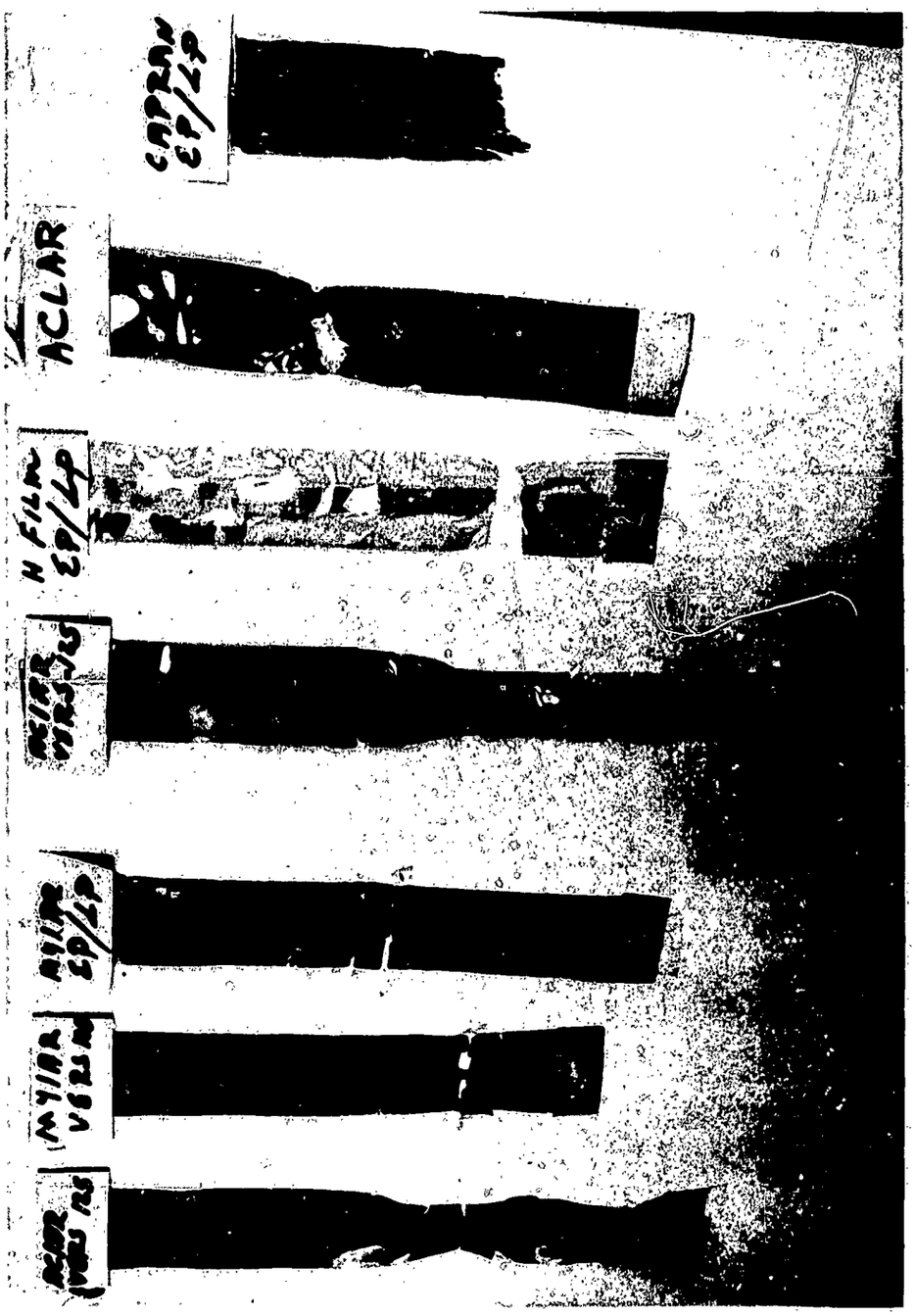


Figure 6. Photograph of Membranes After Stressing

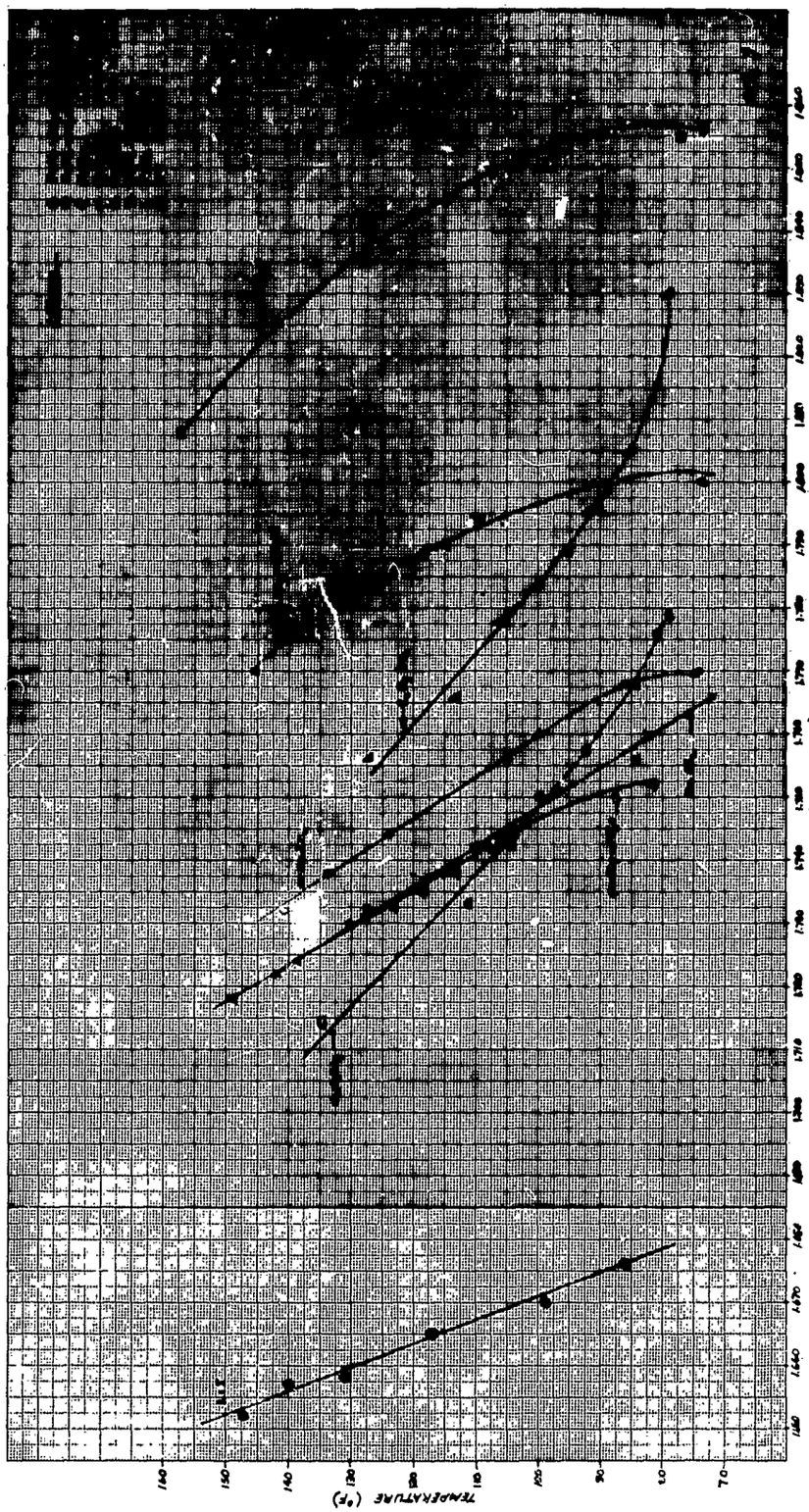


Figure 7. Filler Fluids, Temperature - Density Curves

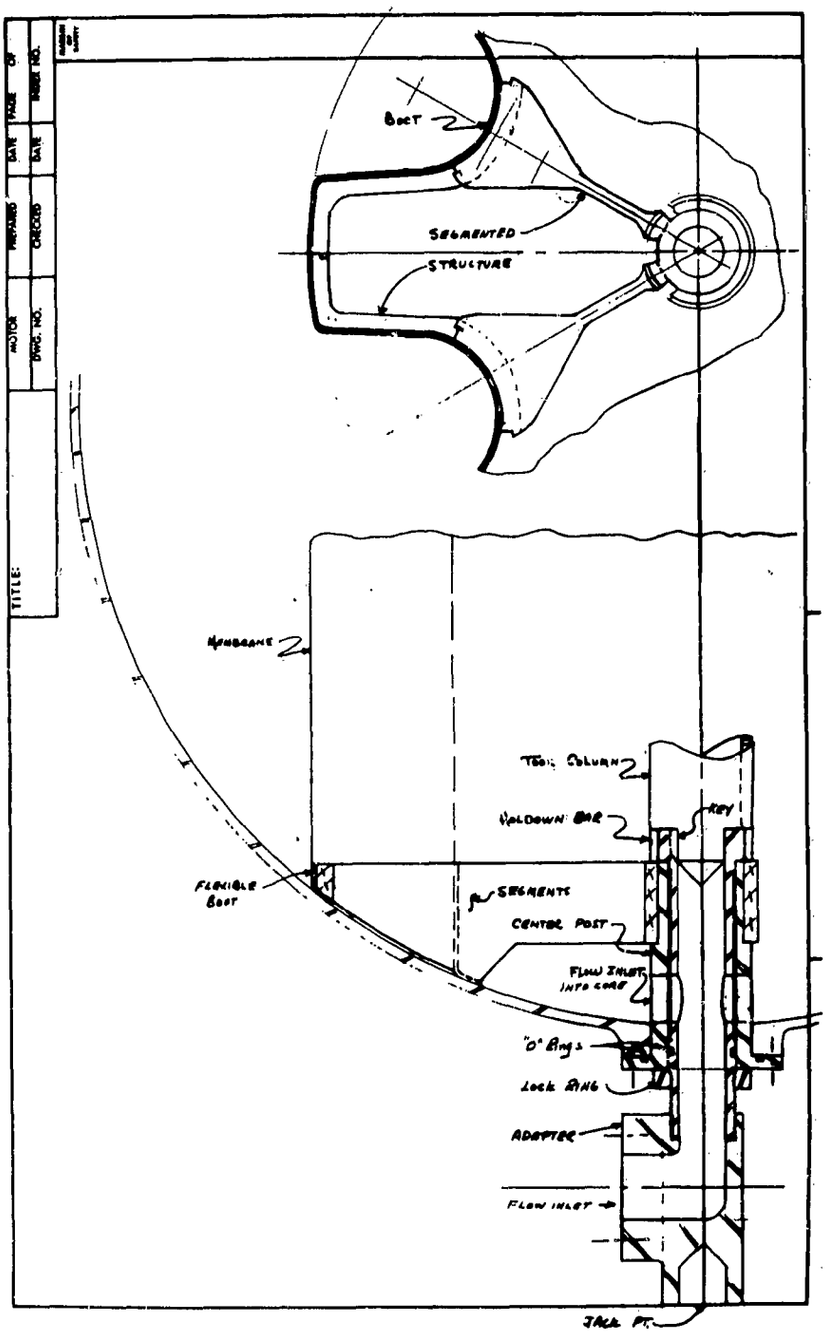


Figure 8. Membrane Core - Head-End Design

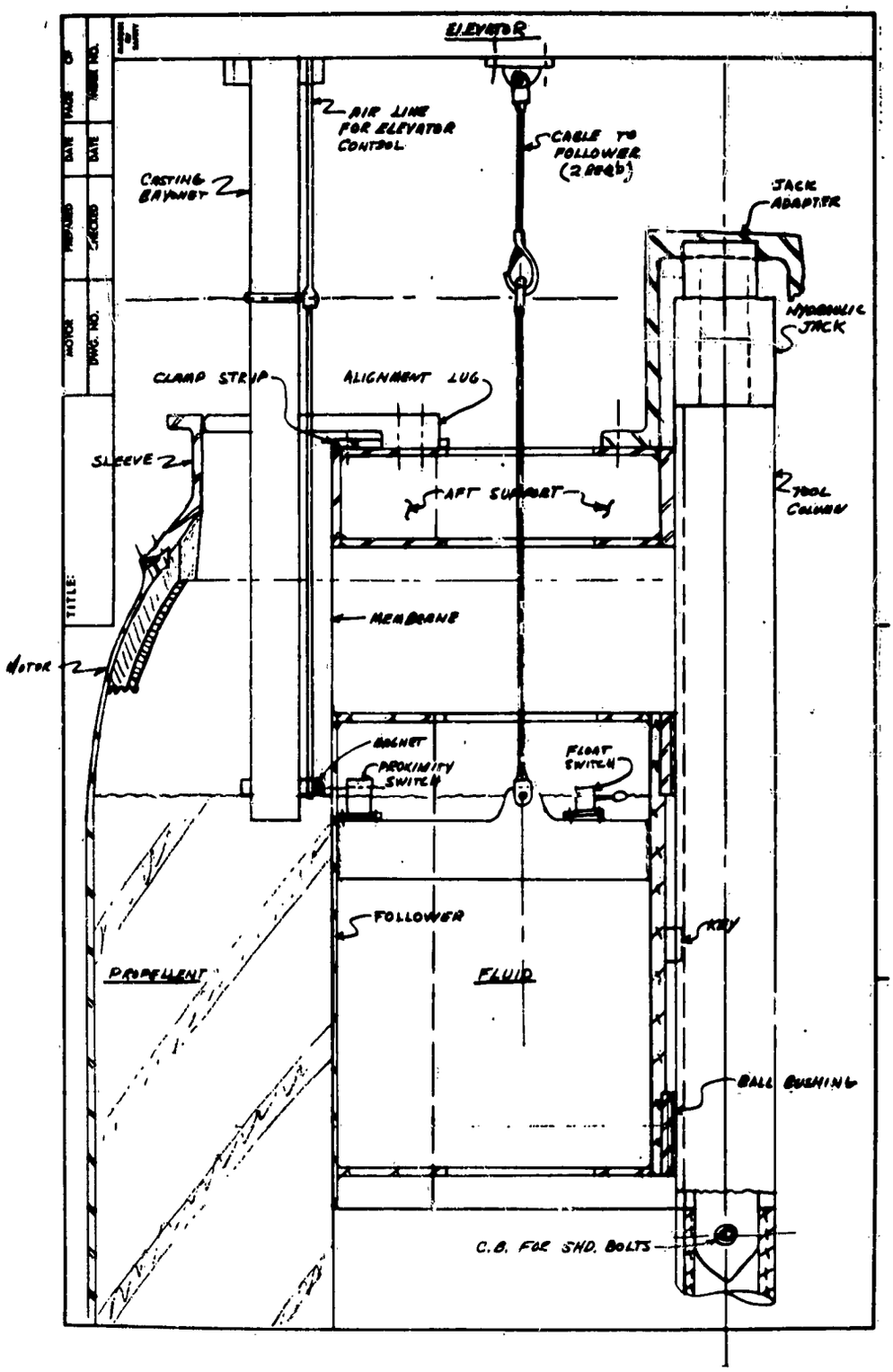


Figure 9. Membrane Core - Aft-End Design

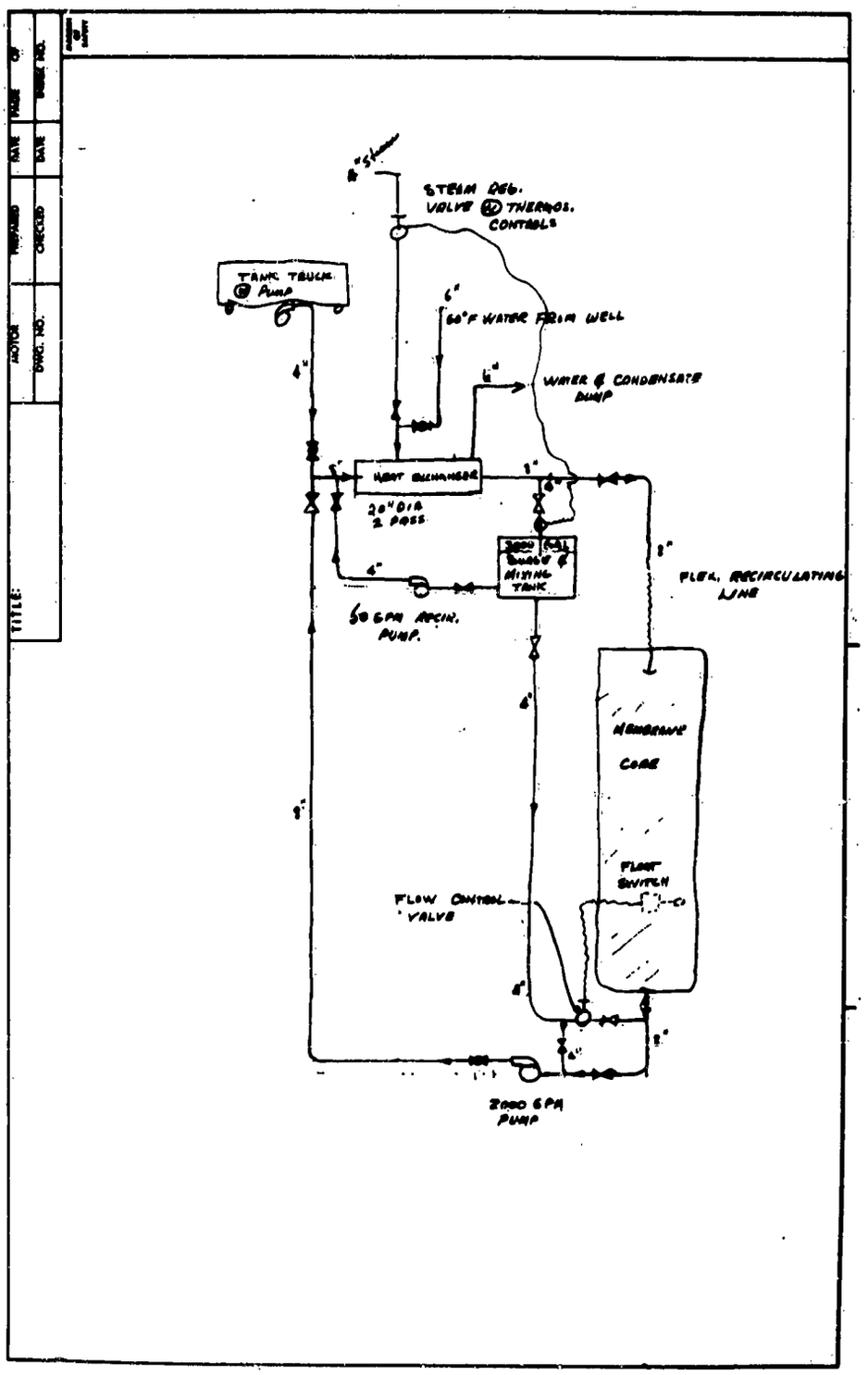


Figure 10. Control Layout

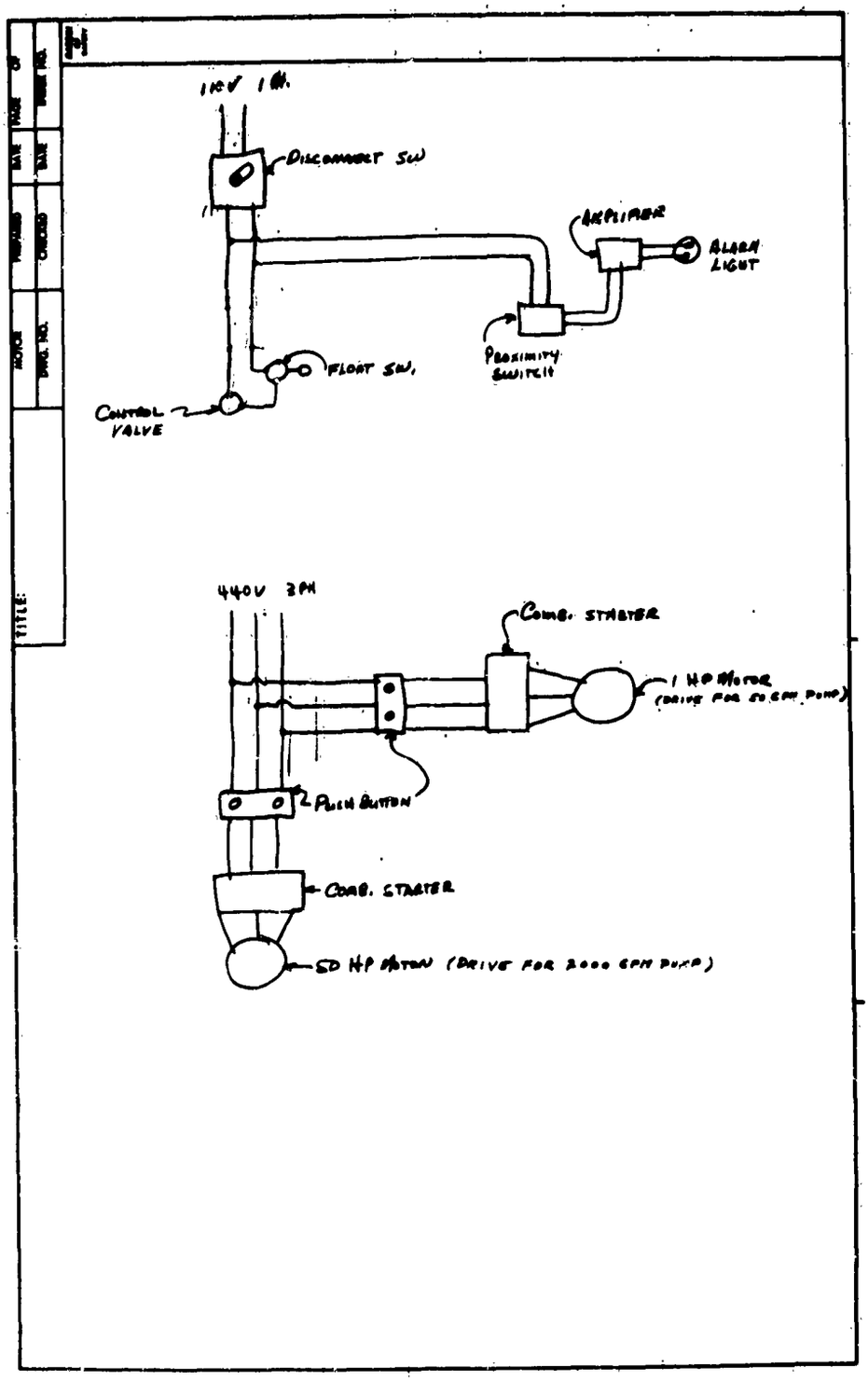


Figure 11. Schematic of Electical Connections

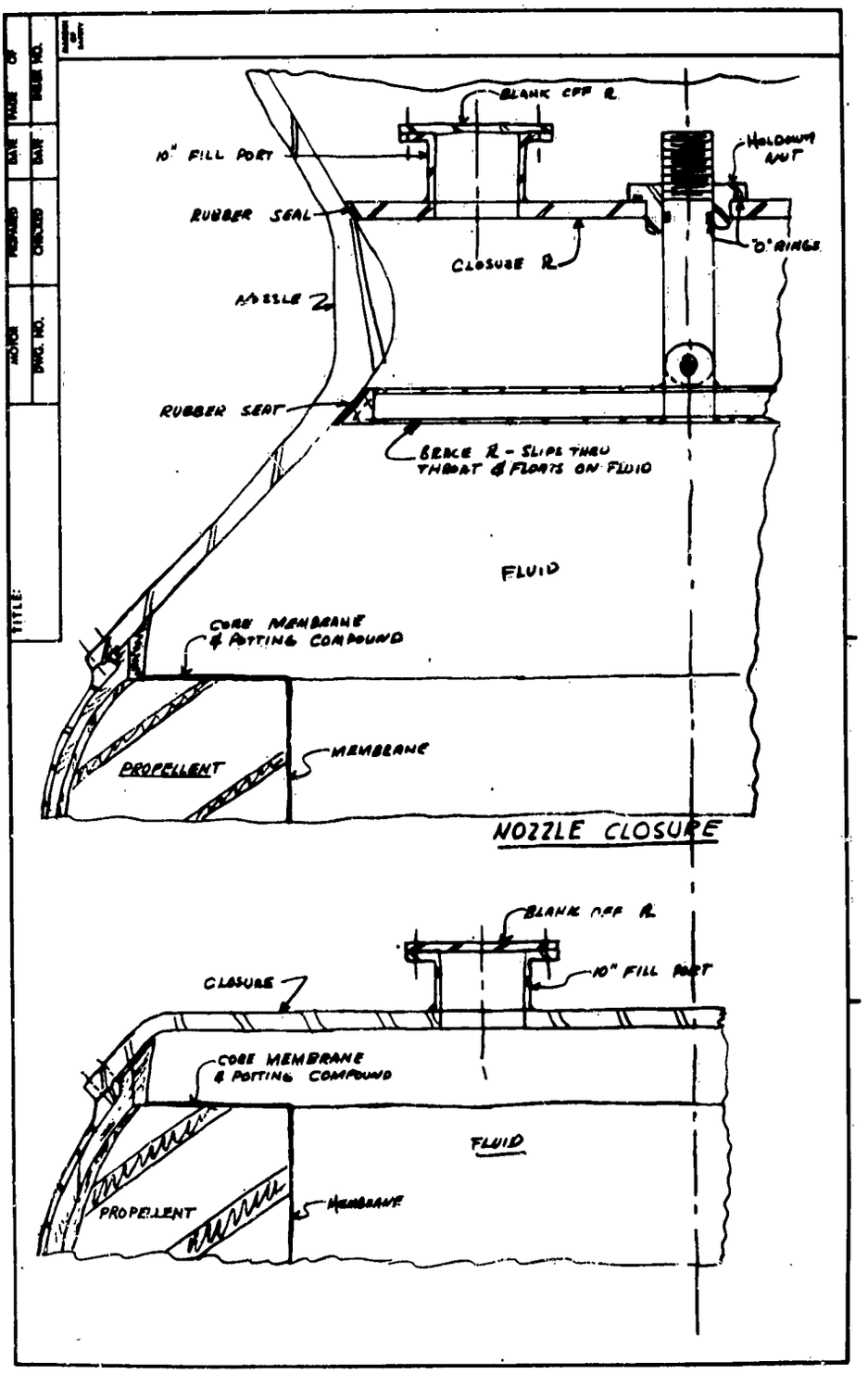


Figure 12. Membrane Core - Case Closure

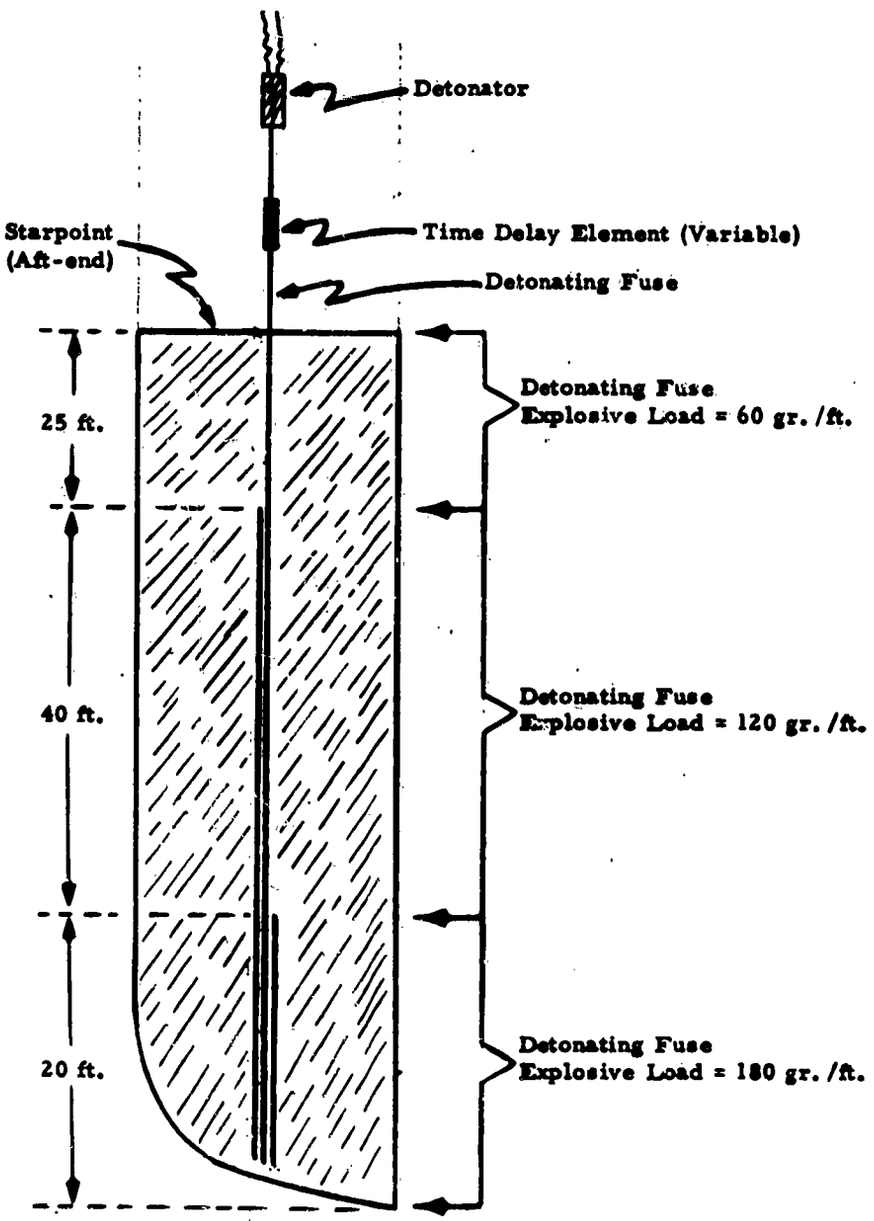


Figure 13. Cross Section of Frangible Core Starpoint Showing Fragmentation Sy

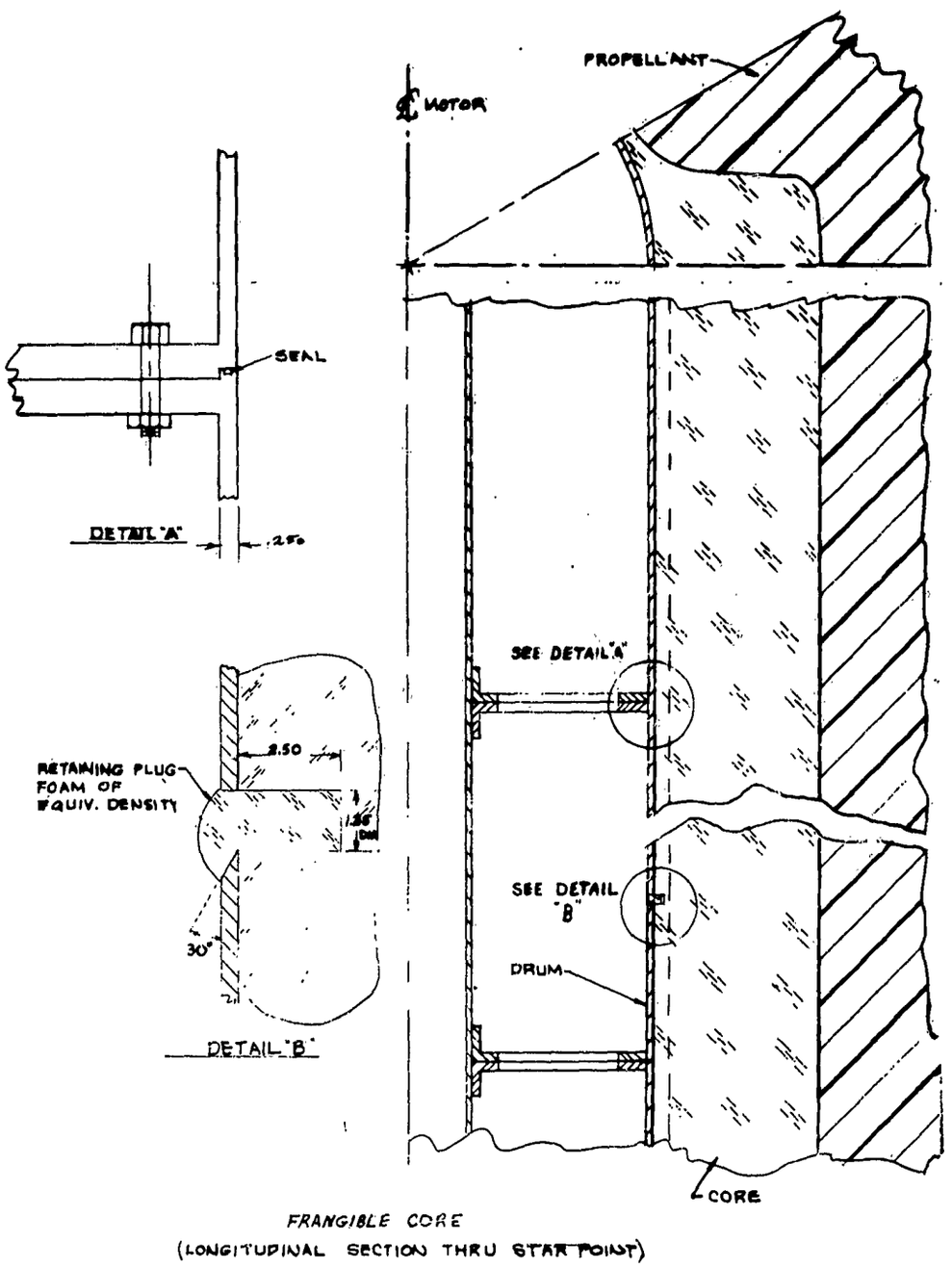


Figure 14. Sketch of Frangible Core - Longitudinal Section through Starpoint

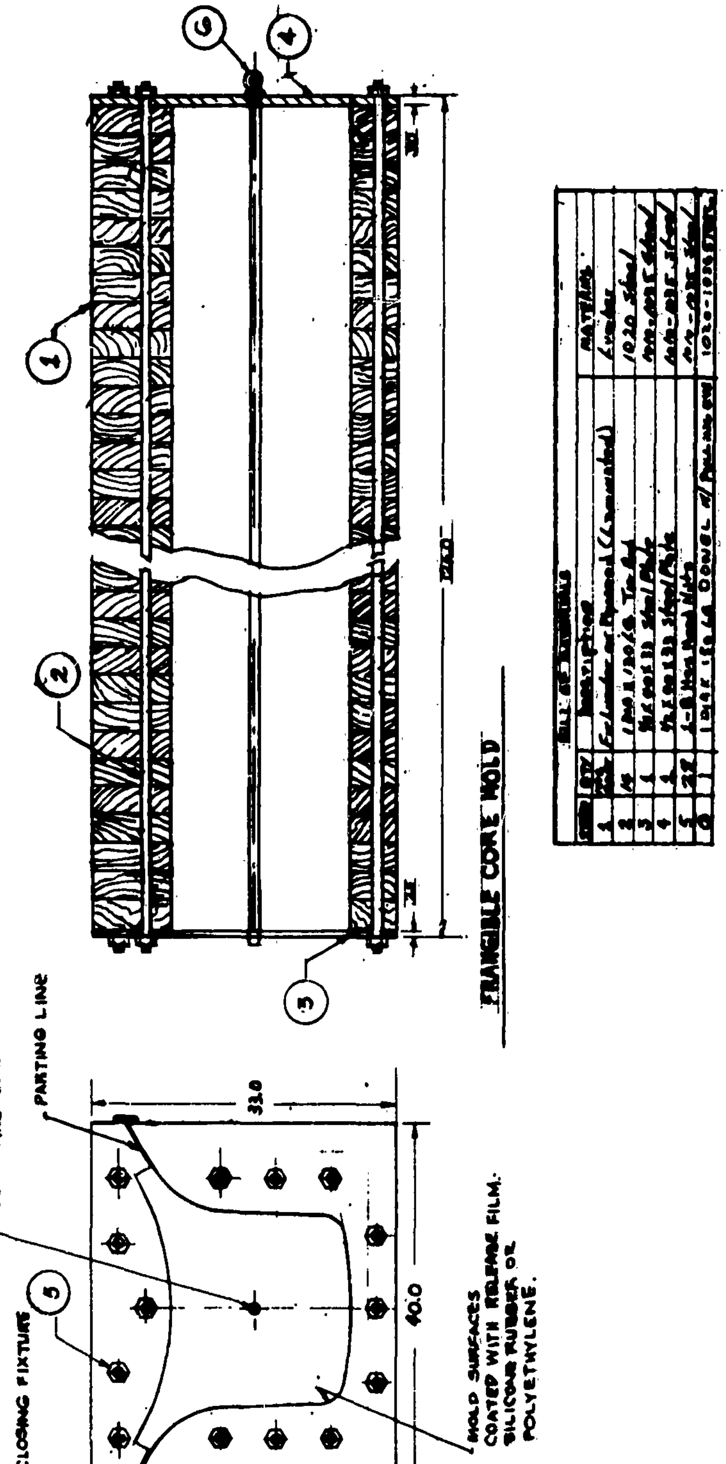


Figure 15. Sketch of Frangible Core Mold

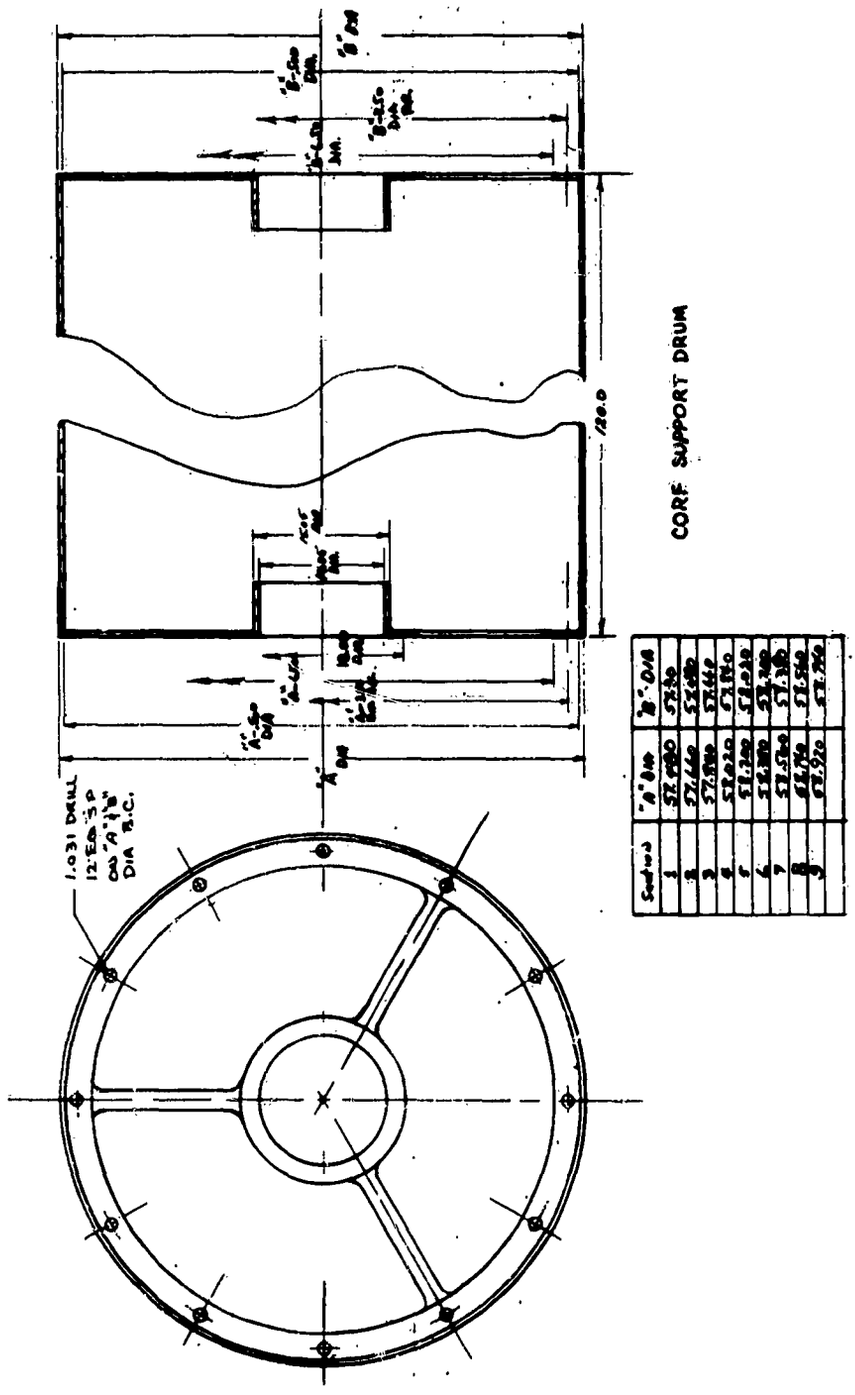


Figure 16. Core Support Drum

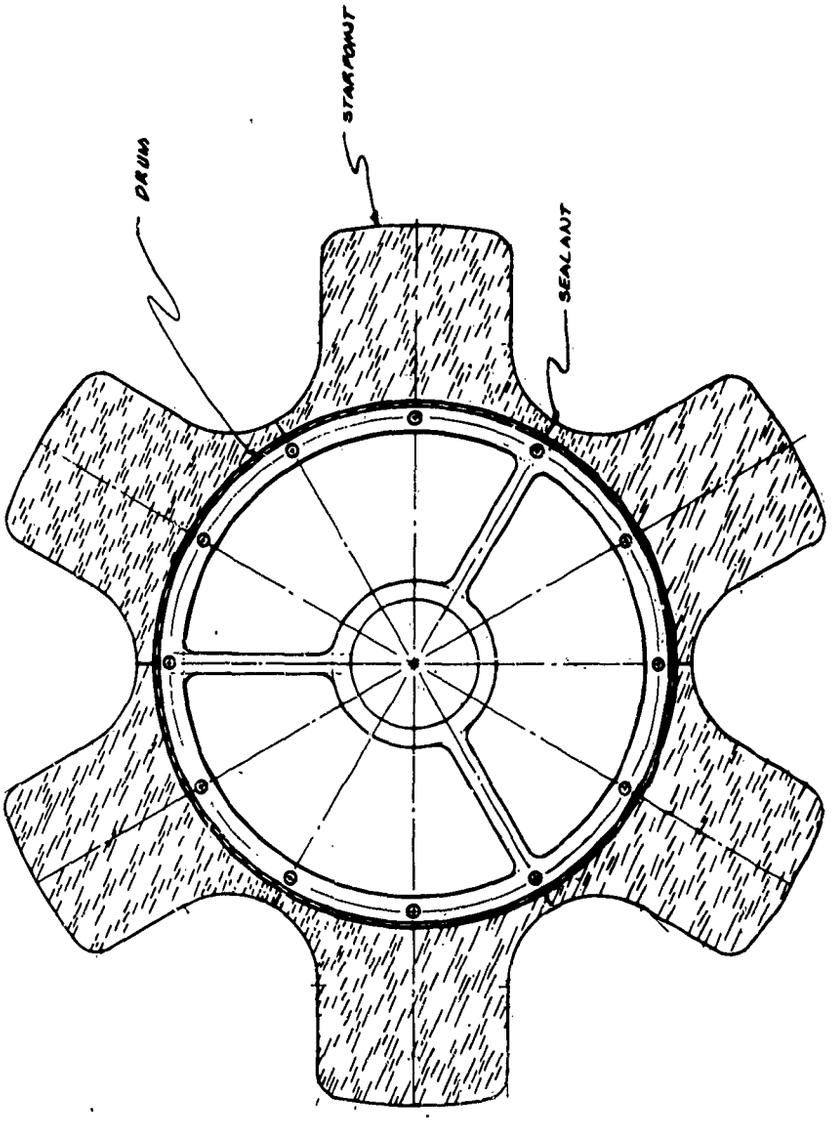


Figure 17. Cross Section of Formed Starpoints and Positioning Drum

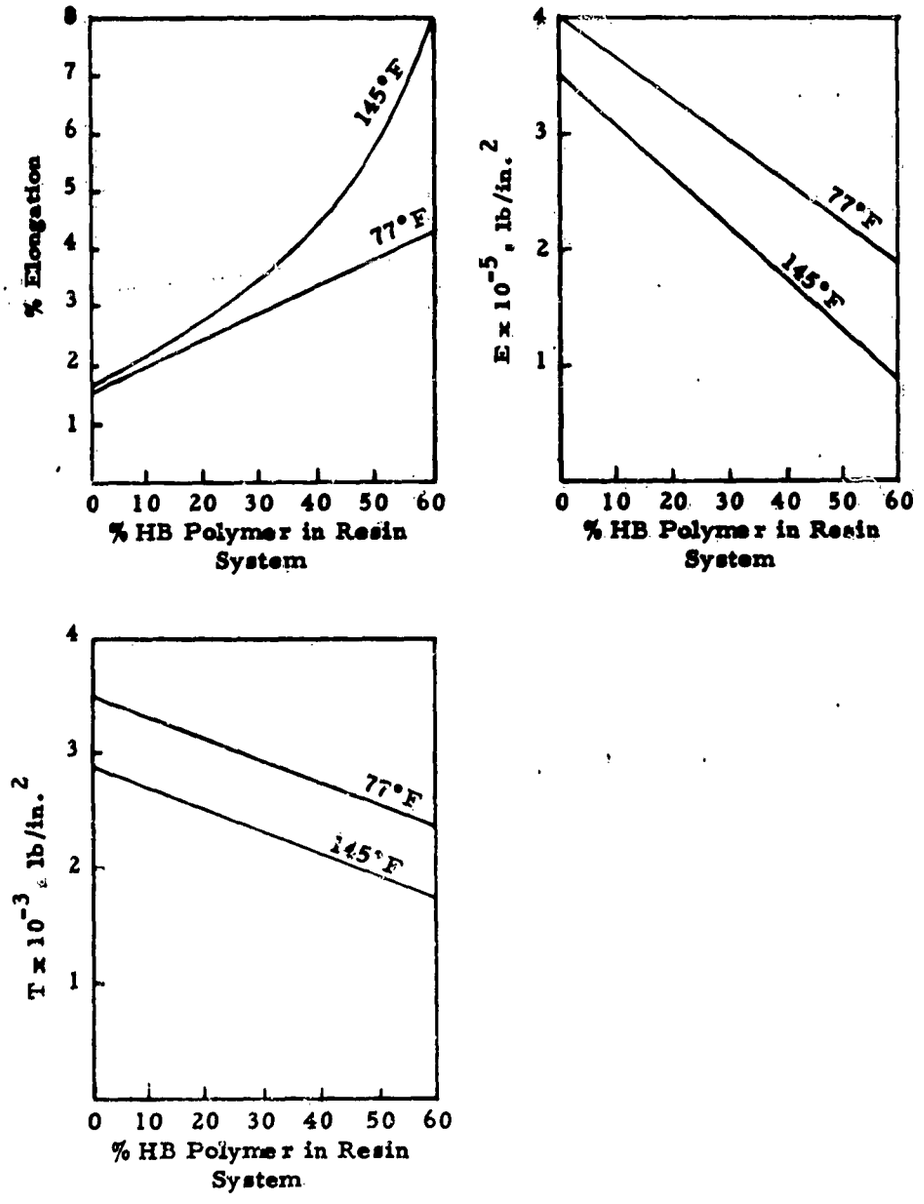


Figure 18. Effect of Percent of HB Polymer on Physical Properties of Resin System

Figure 19. Coating Equipment

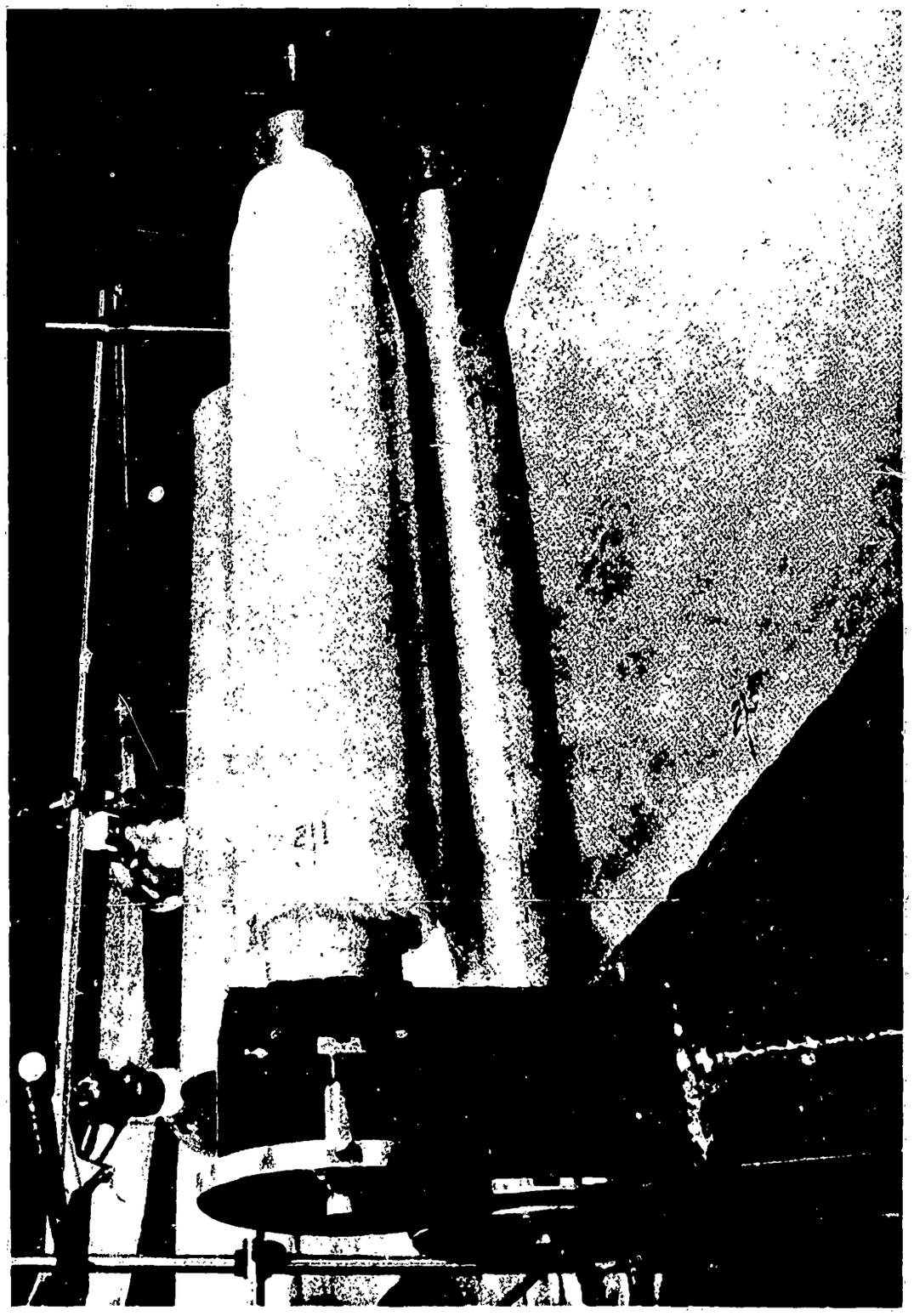


Figure 20. Rewind Equipment

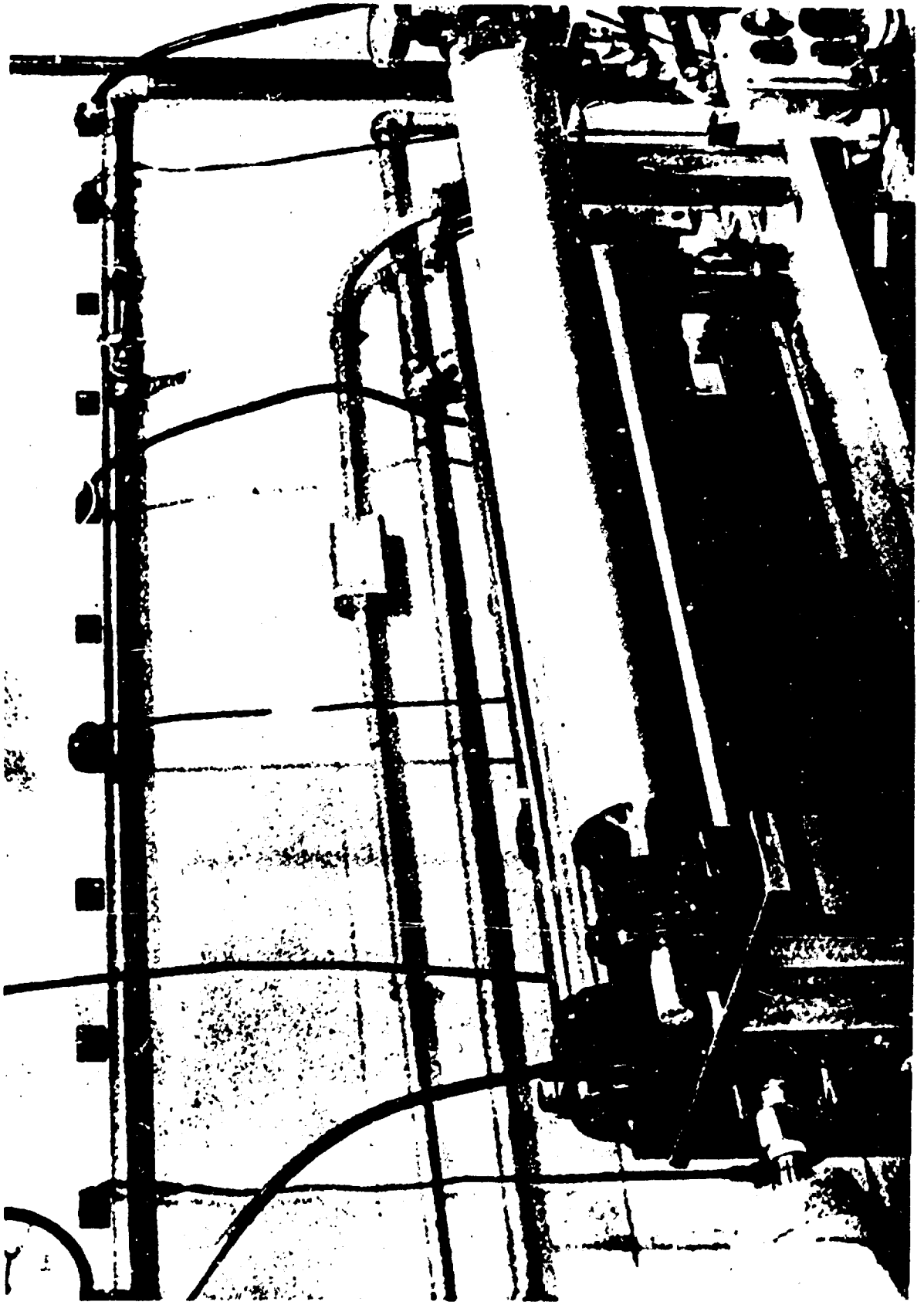


Figure 21. Convolute Wrapping Equipment

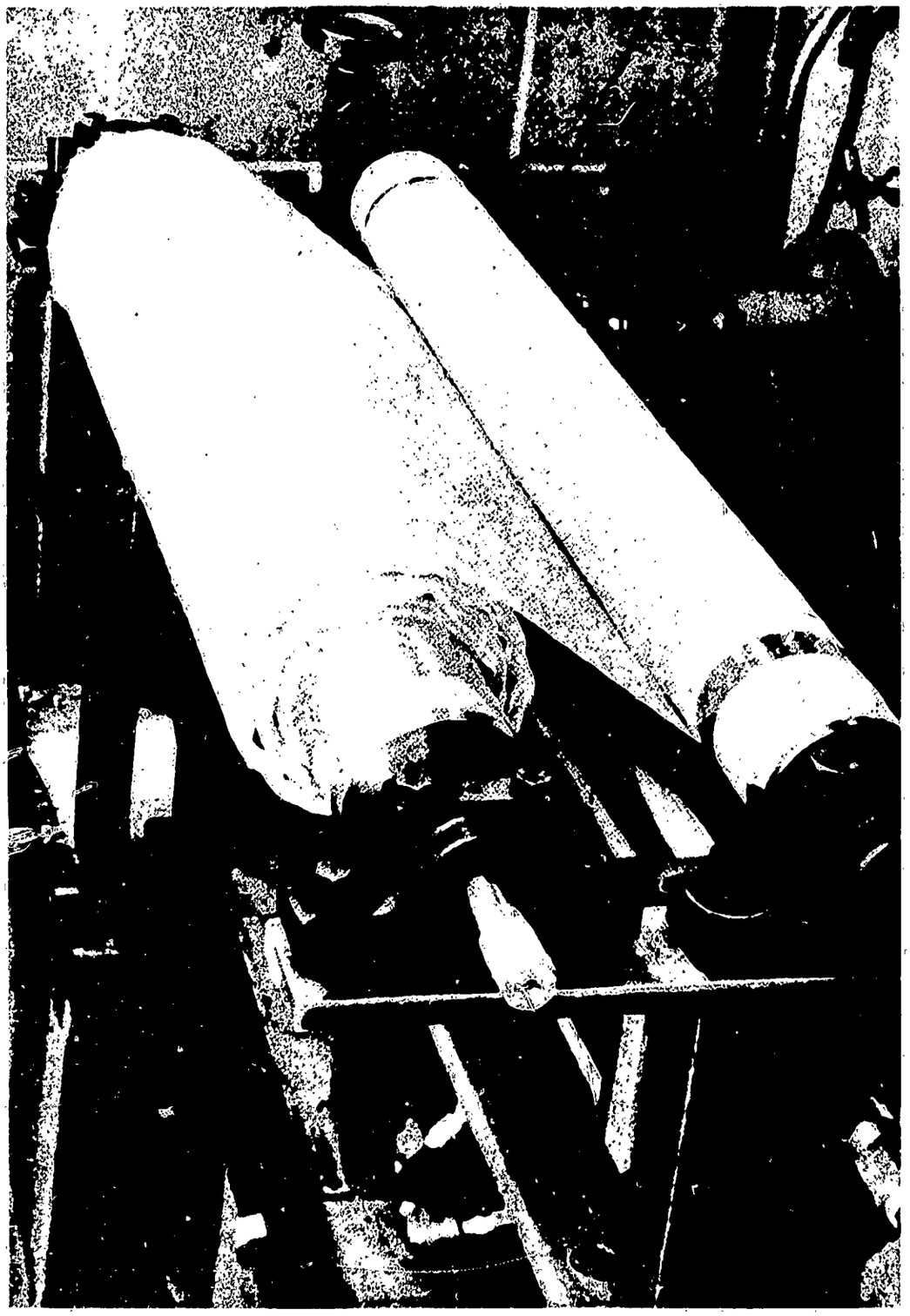


Figure 22. Core Wrapped on Mandrel

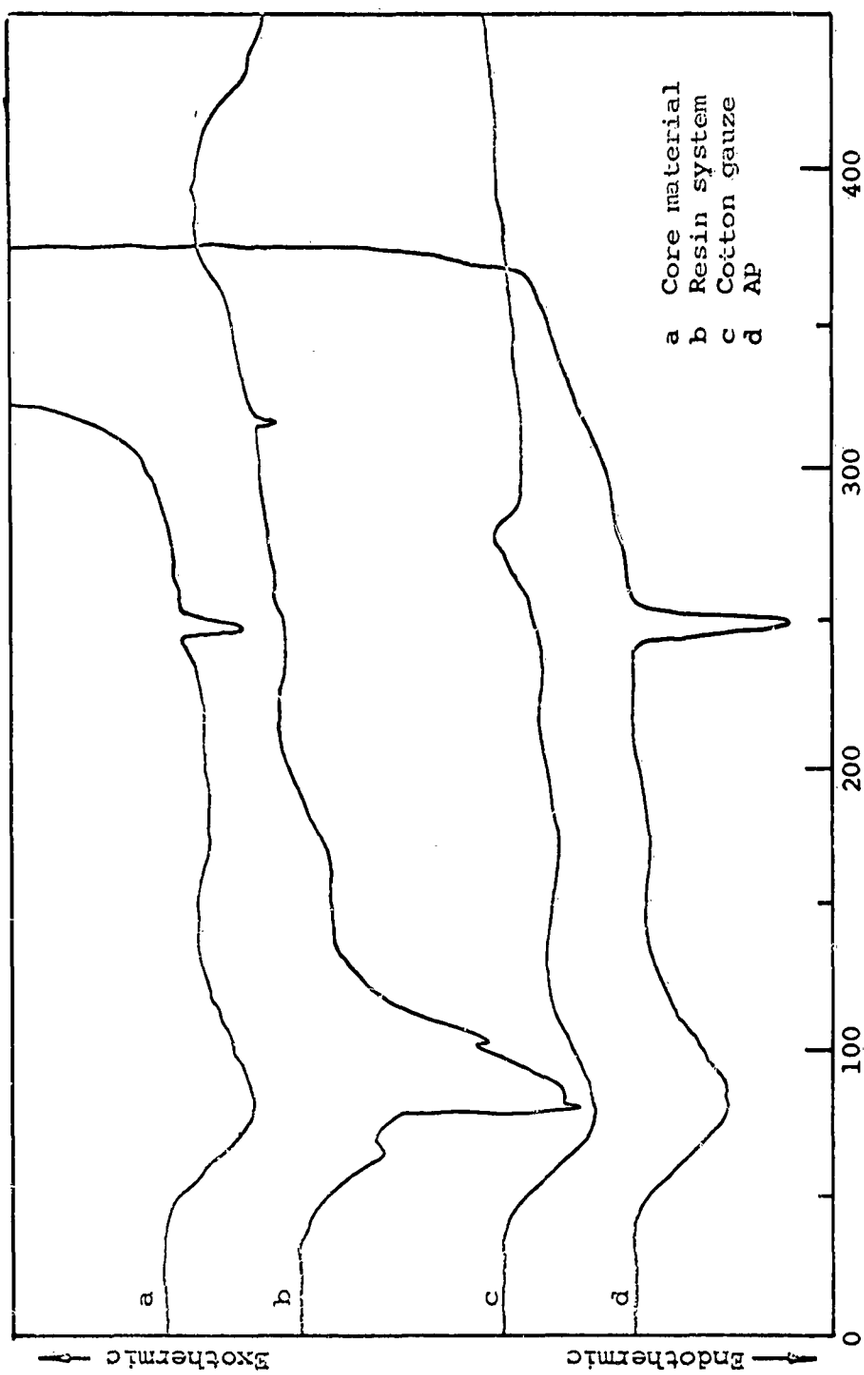


Figure 23. DTA Curves of Combustible Core Ingredients

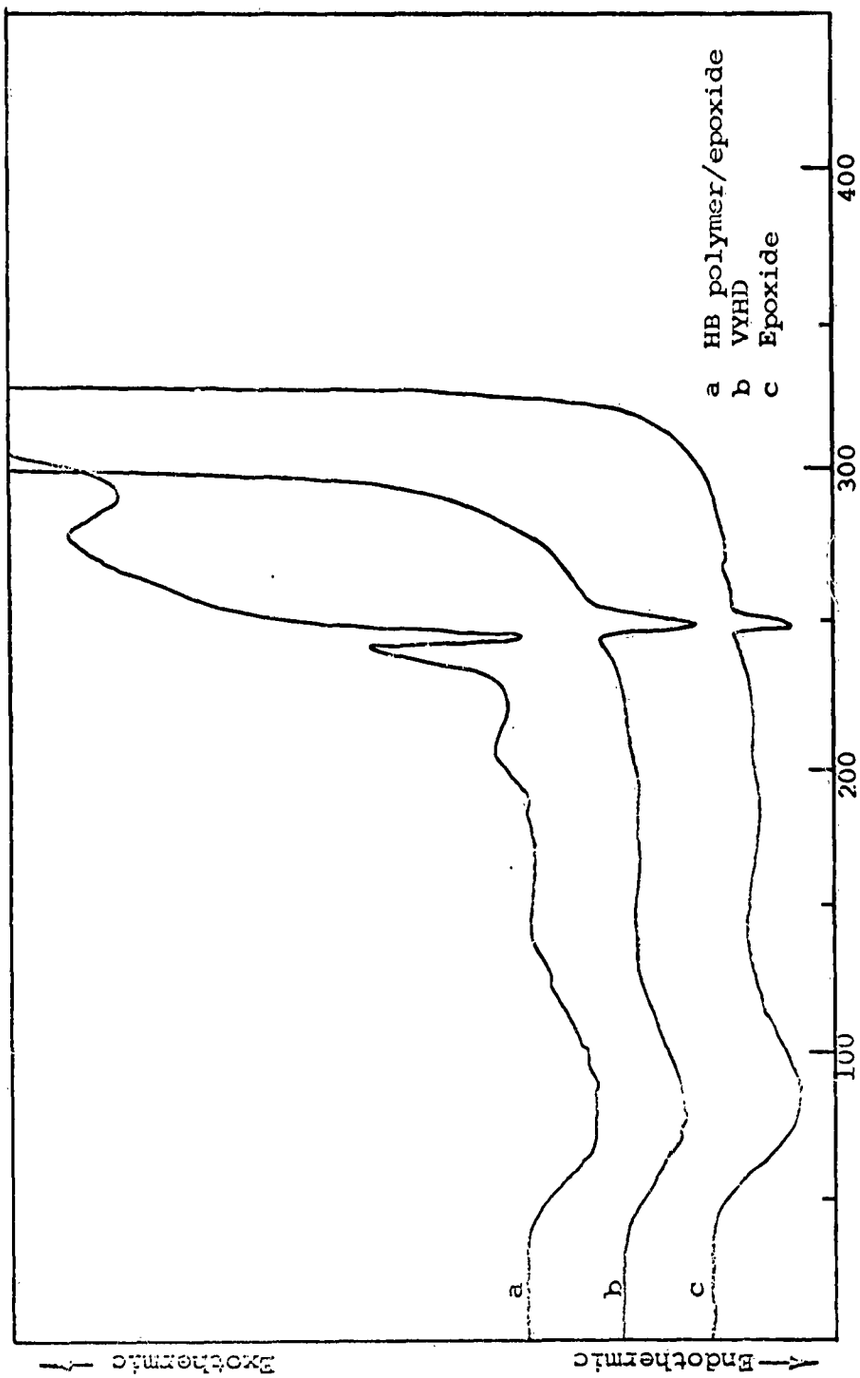


Figure 24. DTA Curves of Combustible Core Systems

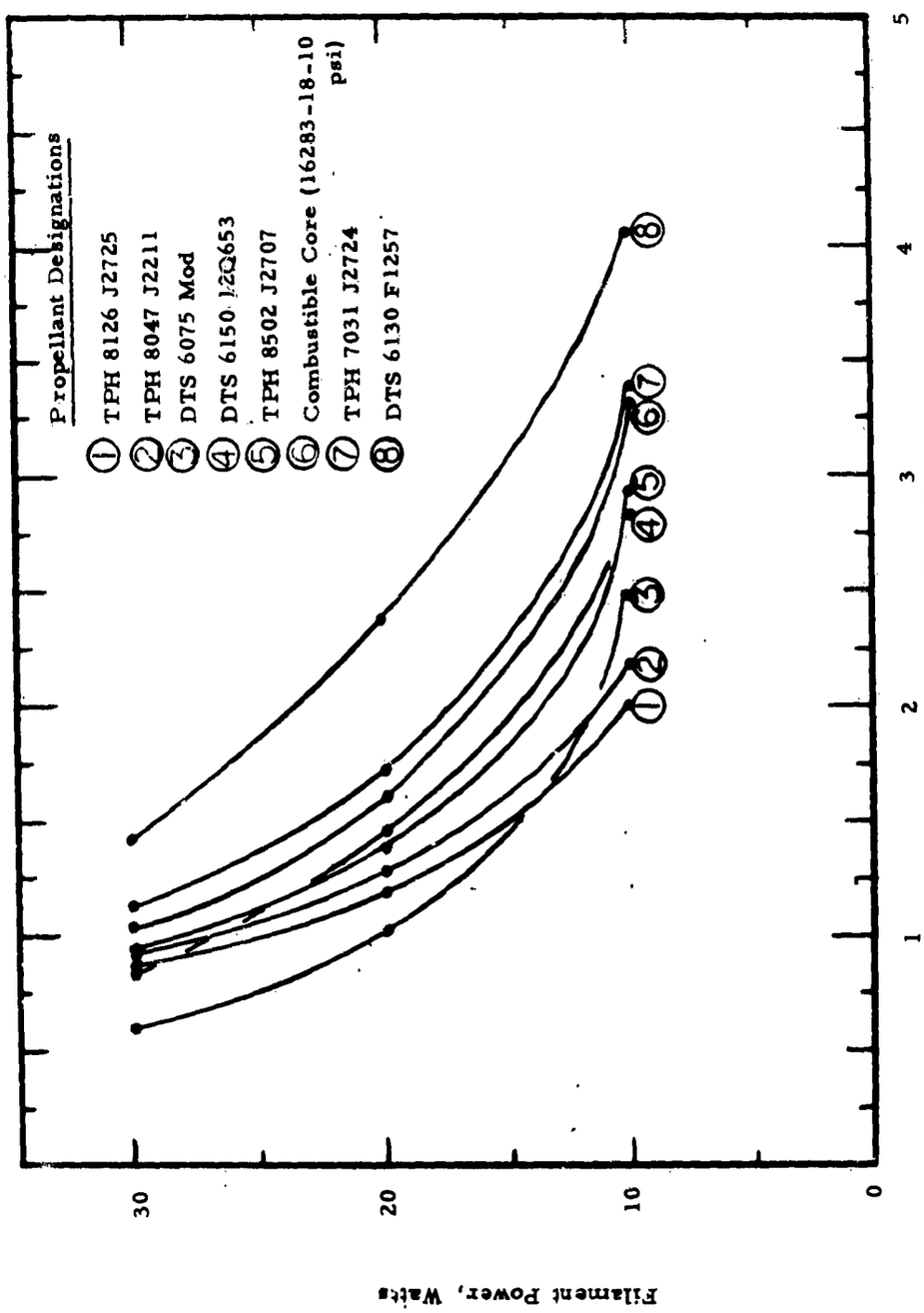


Figure 25. Filament Power Versus Propellant Ignition Delay

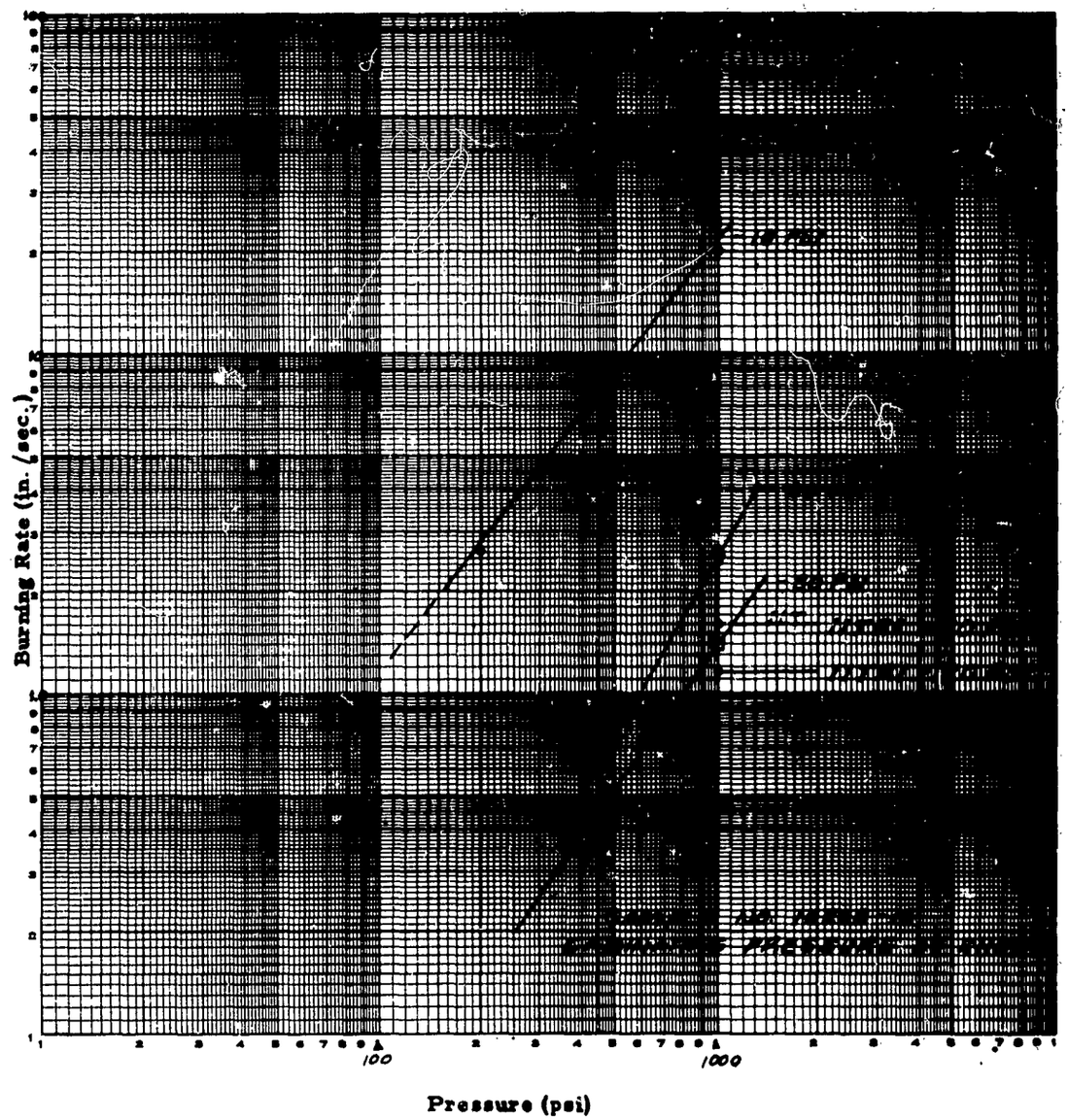


Figure 26. Comparison of IITRI and Thiokol Burning Rate Data

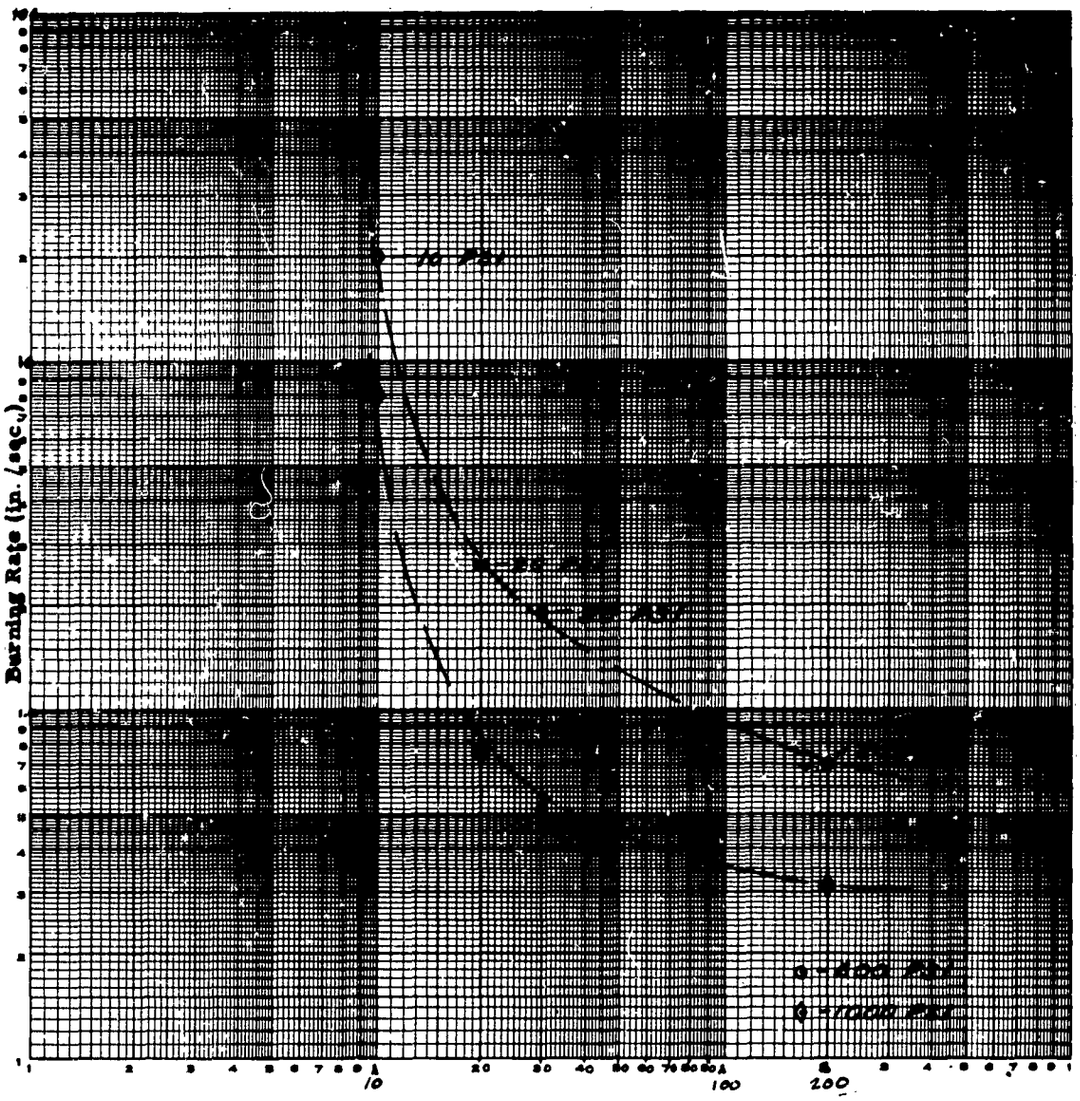


Figure 27. Burning Rates Versus Laminating Pressure at 60% Oxidizer Content (Thiokol Data)

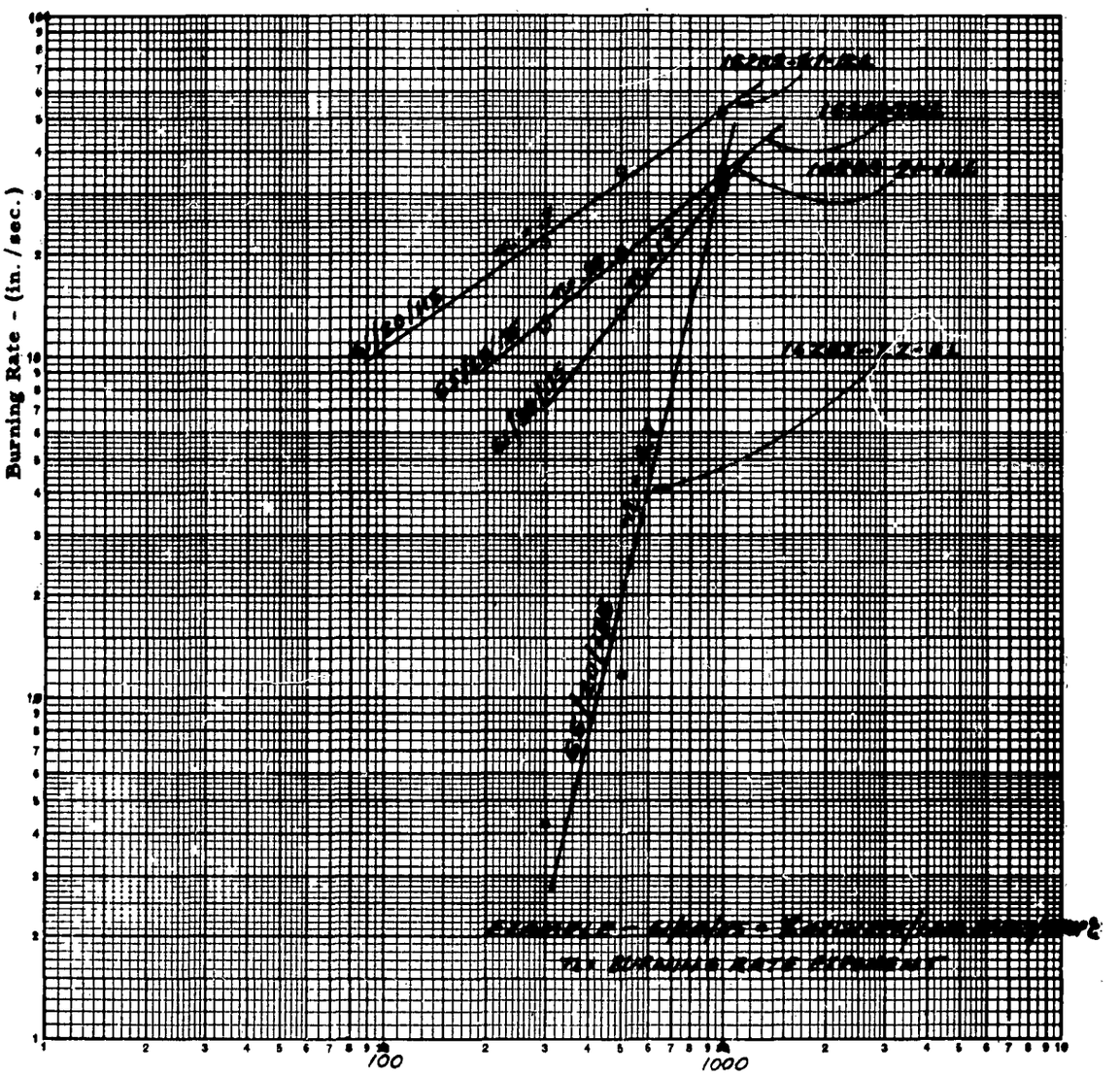


Figure 28. Variations in Burning Rate and Exponent with Laminating Pressure, Laminating Temperature and Oxidizer Content

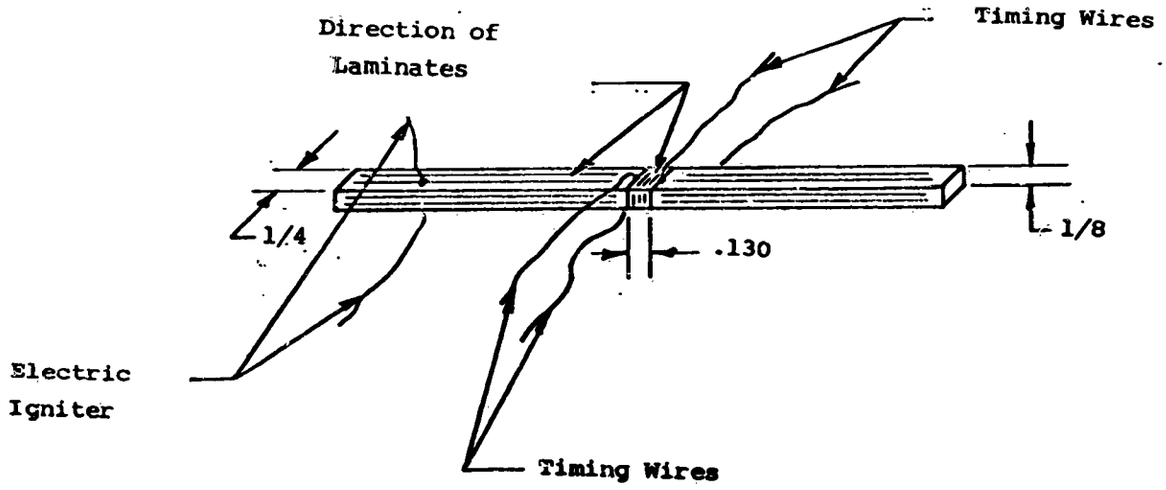


Figure 29. Transverse Burning Rate, Test Method 1

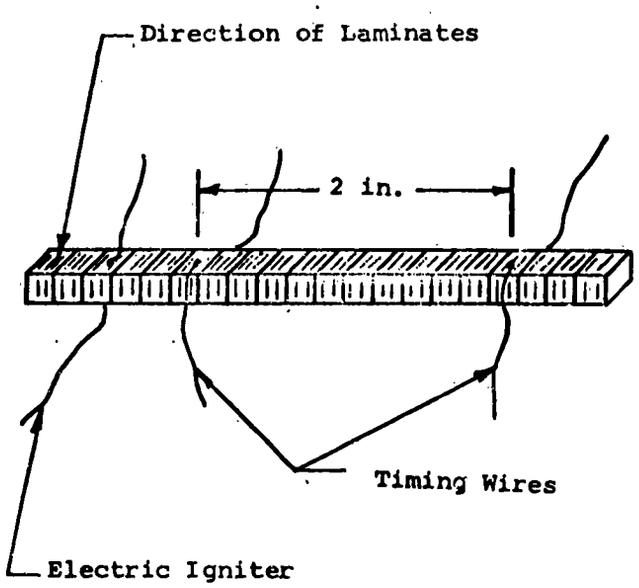


Figure 30. Transverse Burning Rate, Test Method 2

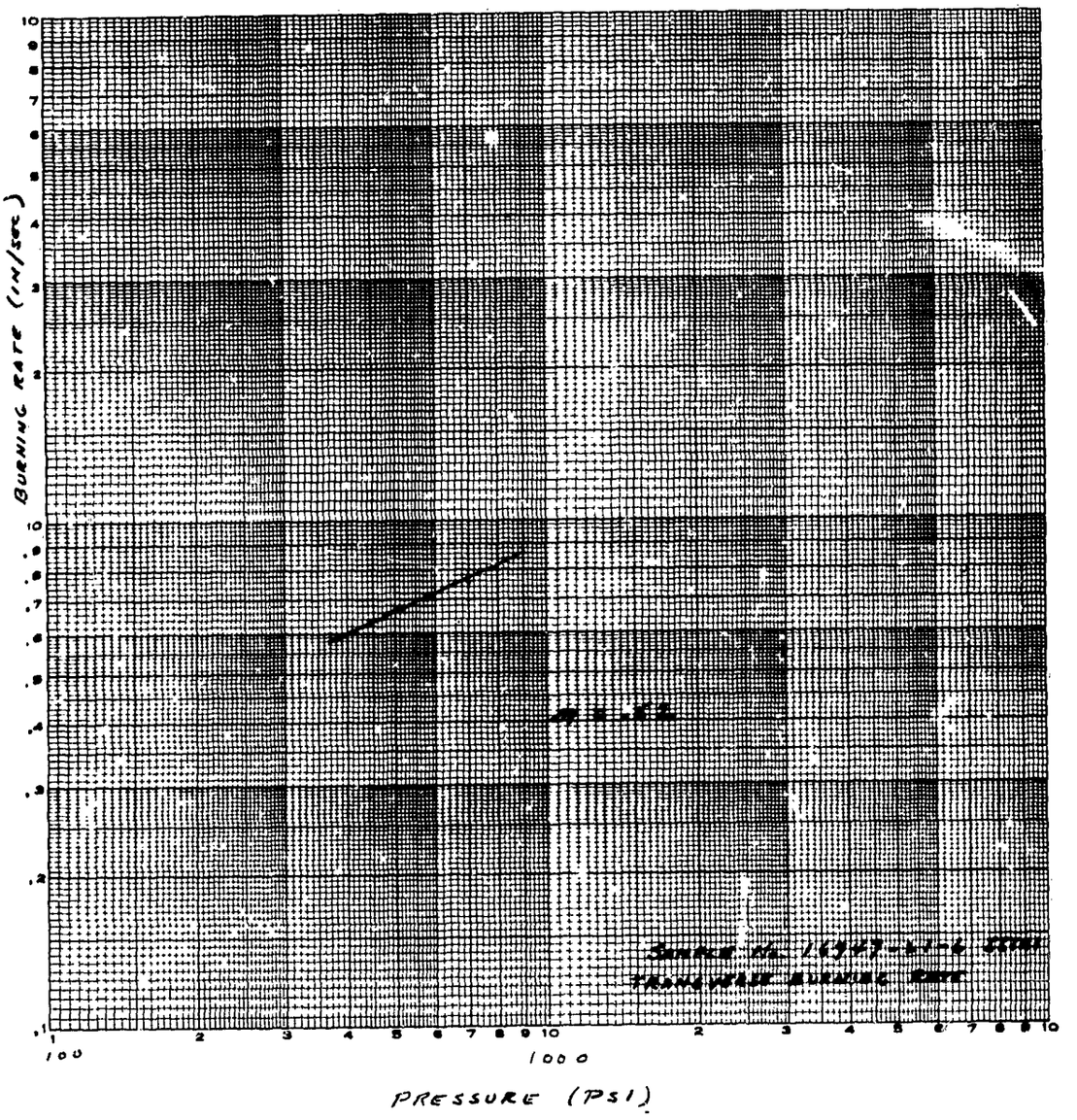


Figure 31. Transverse Burning Rate, IITRI Sample No. 16747-21-6

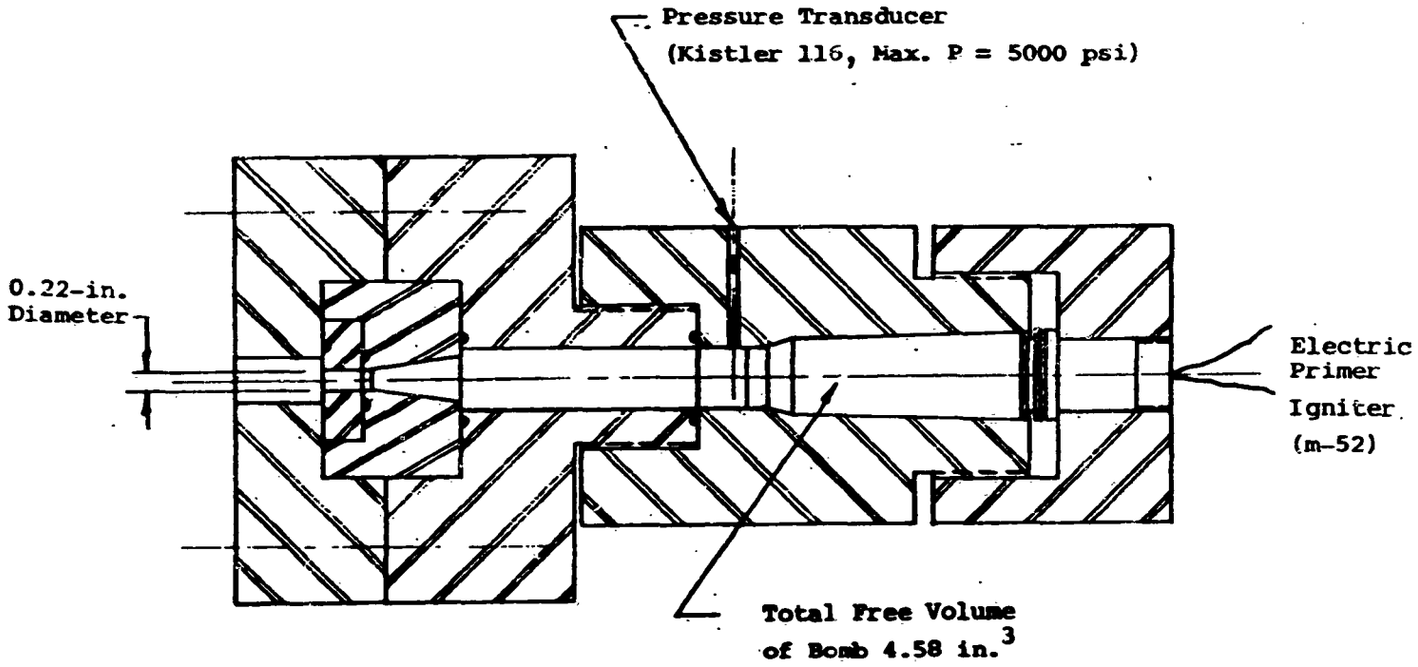


Figure 32. Vented Bomb Test Fixture

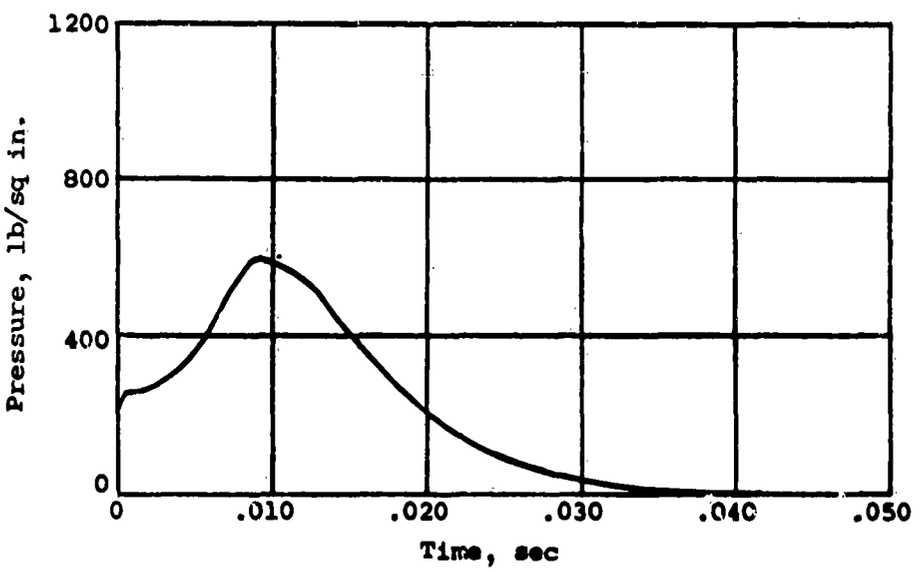


Figure 33. Pressure Versus Time for 1.1 g of M-9 Mortar Flake and Electric Primer

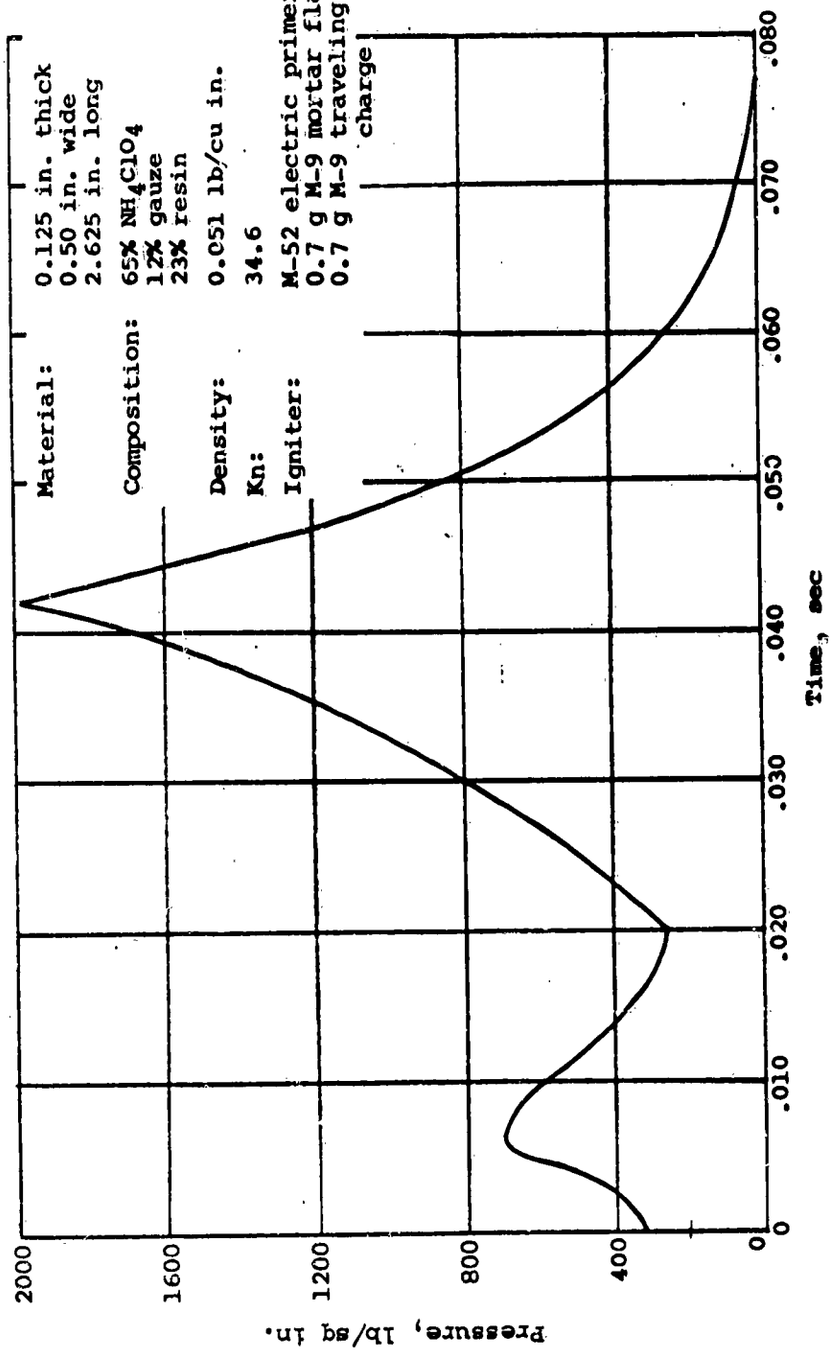


Figure 34. Pressure Versus Time Trace for Combustible Core Material

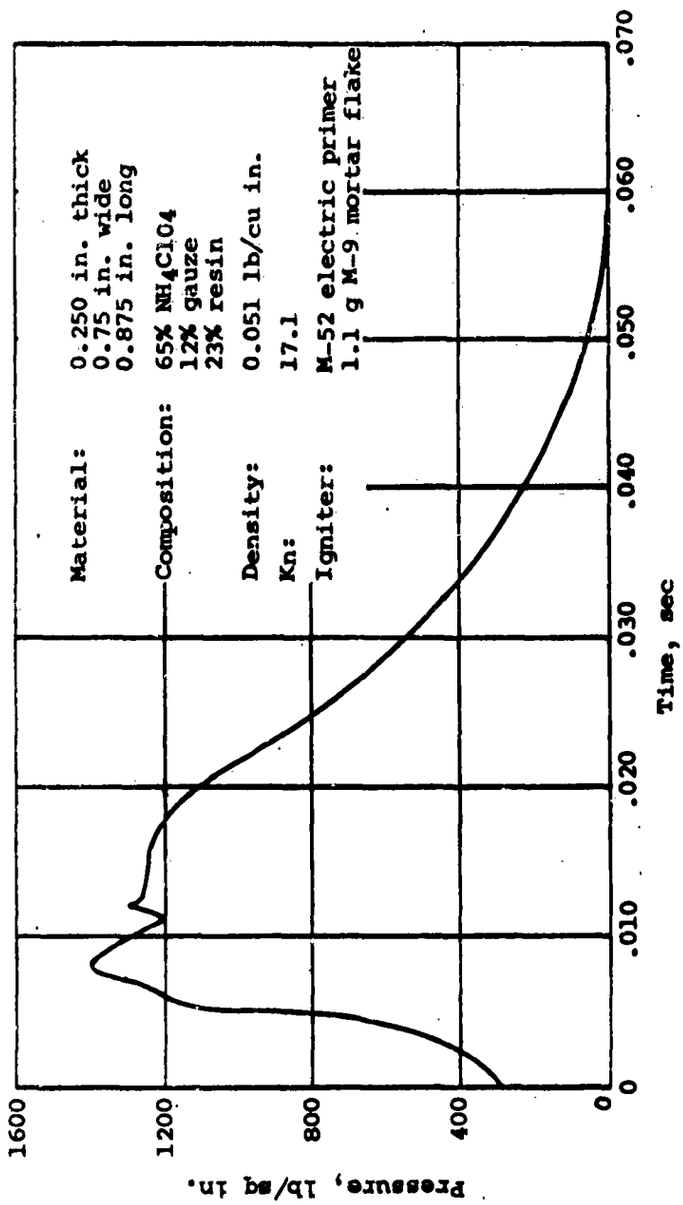


Figure 35. Pressure Versus Time Trace for Combustible Core Material

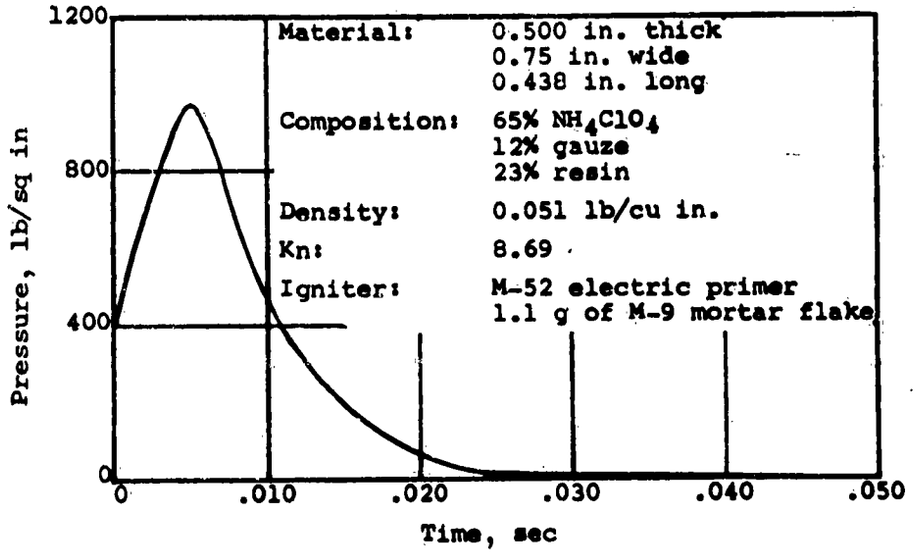


Figure 36. Pressure Versus Time Trace for Combustible Core Material

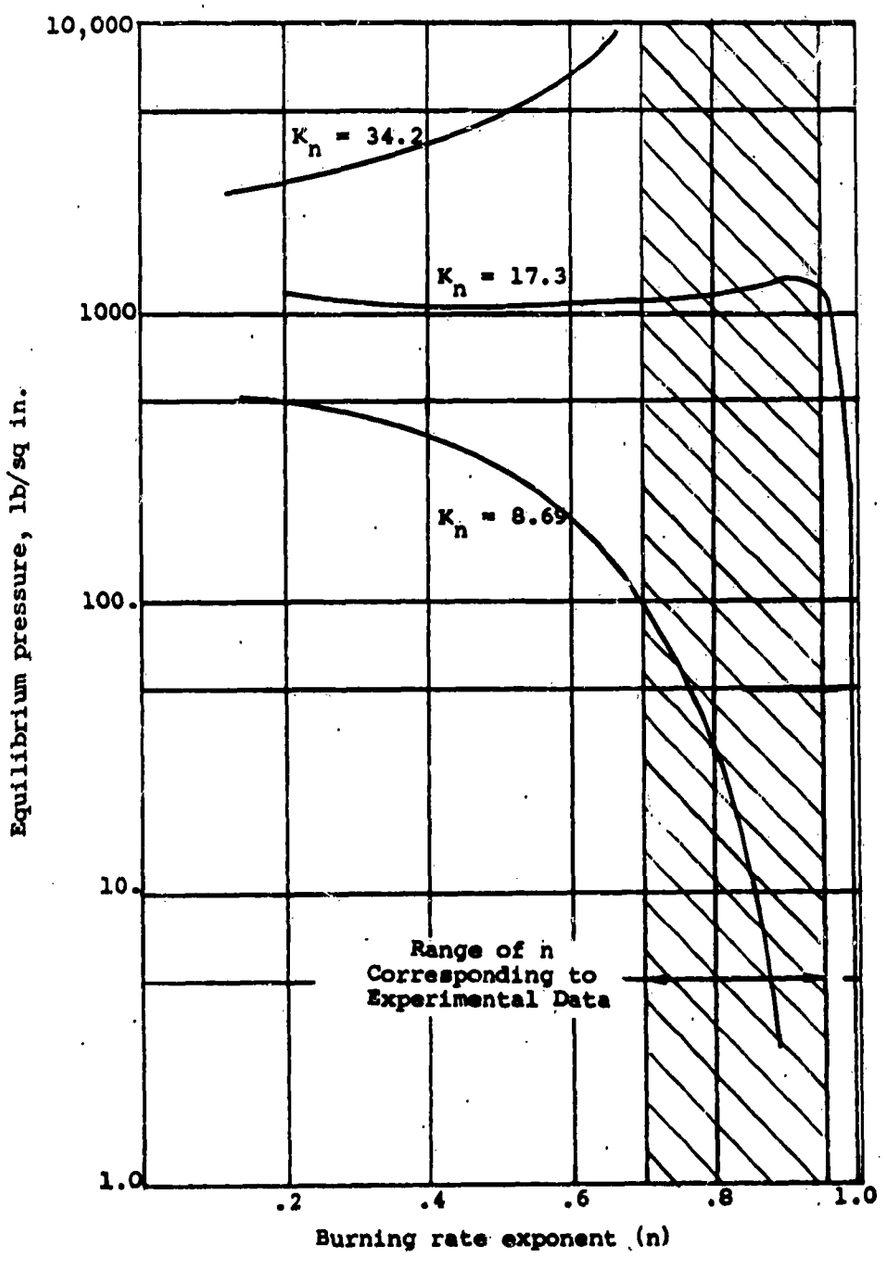


Figure 37. Equilibrium Pressure as a Function of Burning Rate Exponent at Various K_n Values

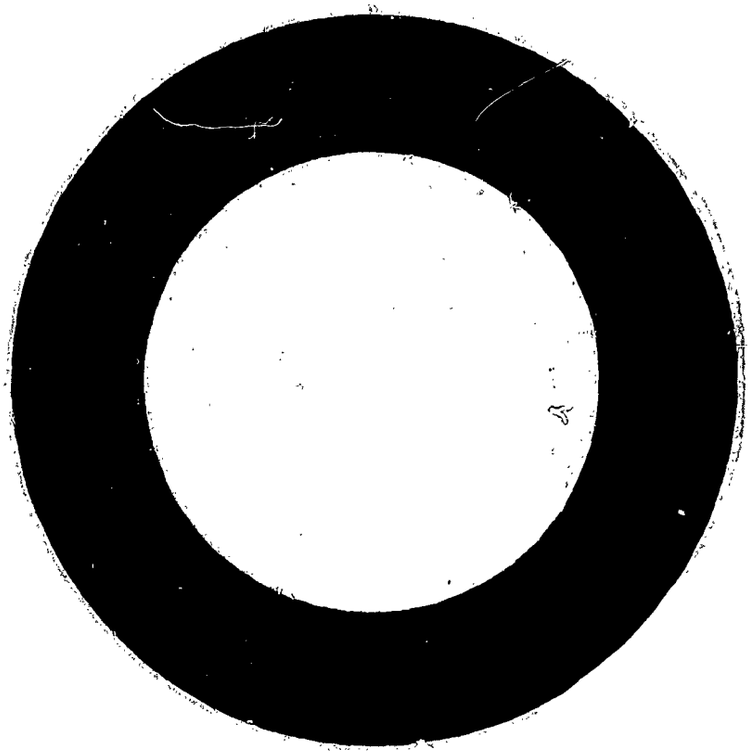


Figure 38. End X-ray View of First IITRI Core (16747-12) Showing Nonhomogeneity

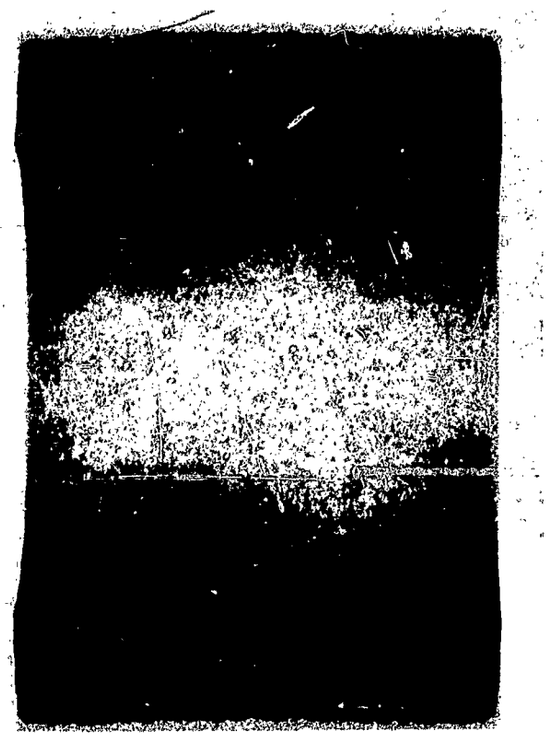


Figure 39. Top X-ray View of First IITRI Core (16747-12) Showing Nonhomogeneity

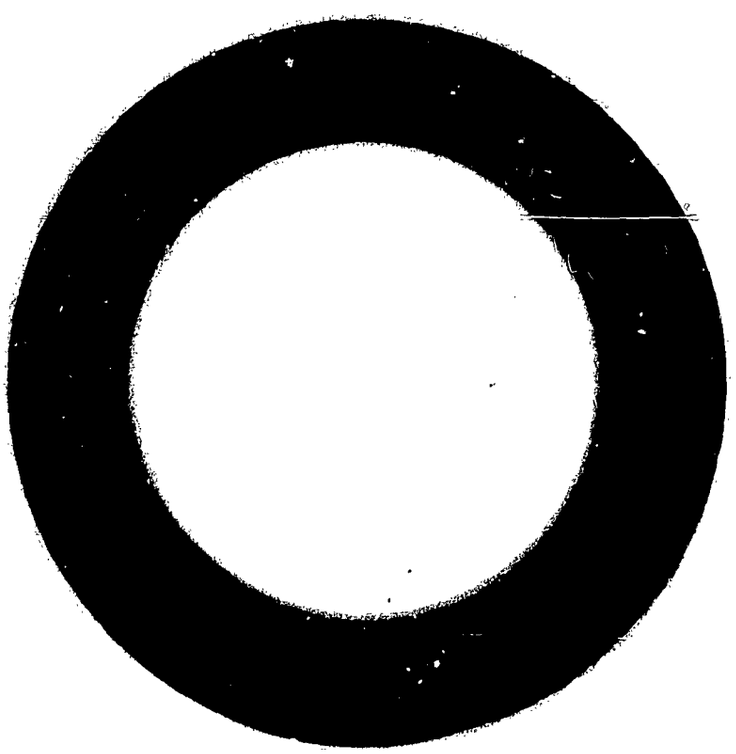


Figure 40. End X-ray View of Second IITRI Core (16747-13) Showing Nonhomogeneity

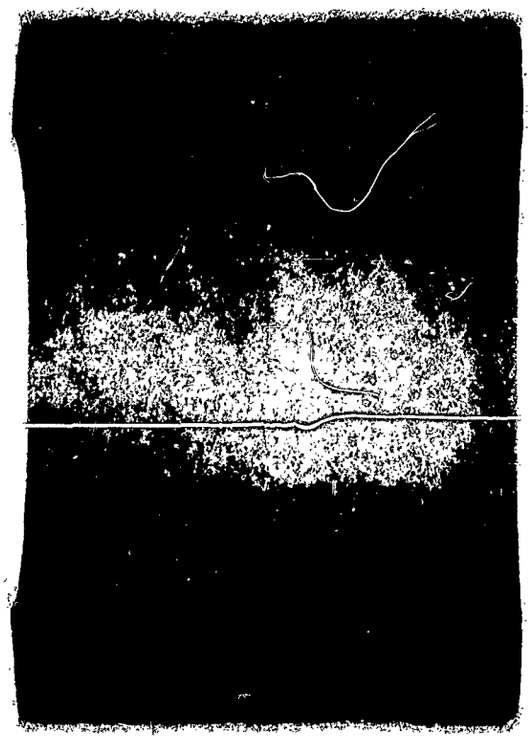


Figure 41. Top X-ray View of Second IITRI Core (16747-13) Showing Nonhomogeneity

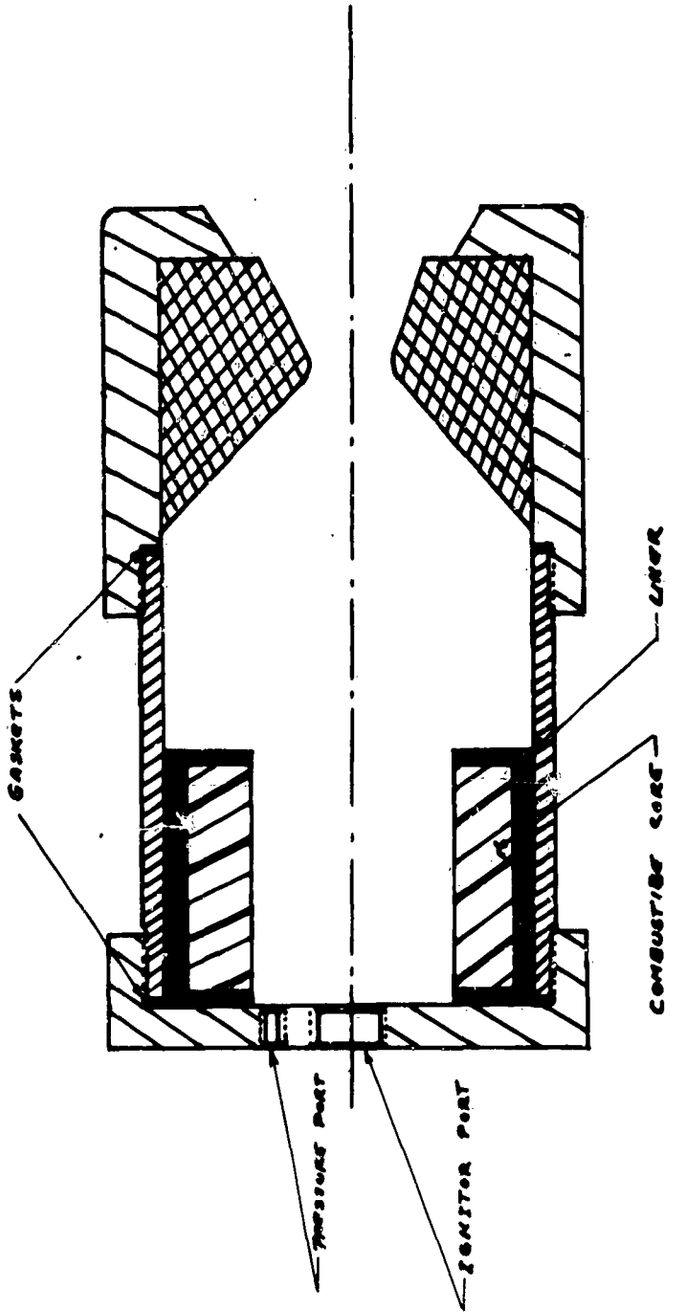


Figure 42. TX11 Motor (6 Inch Case Length) Combustible Core Configuration

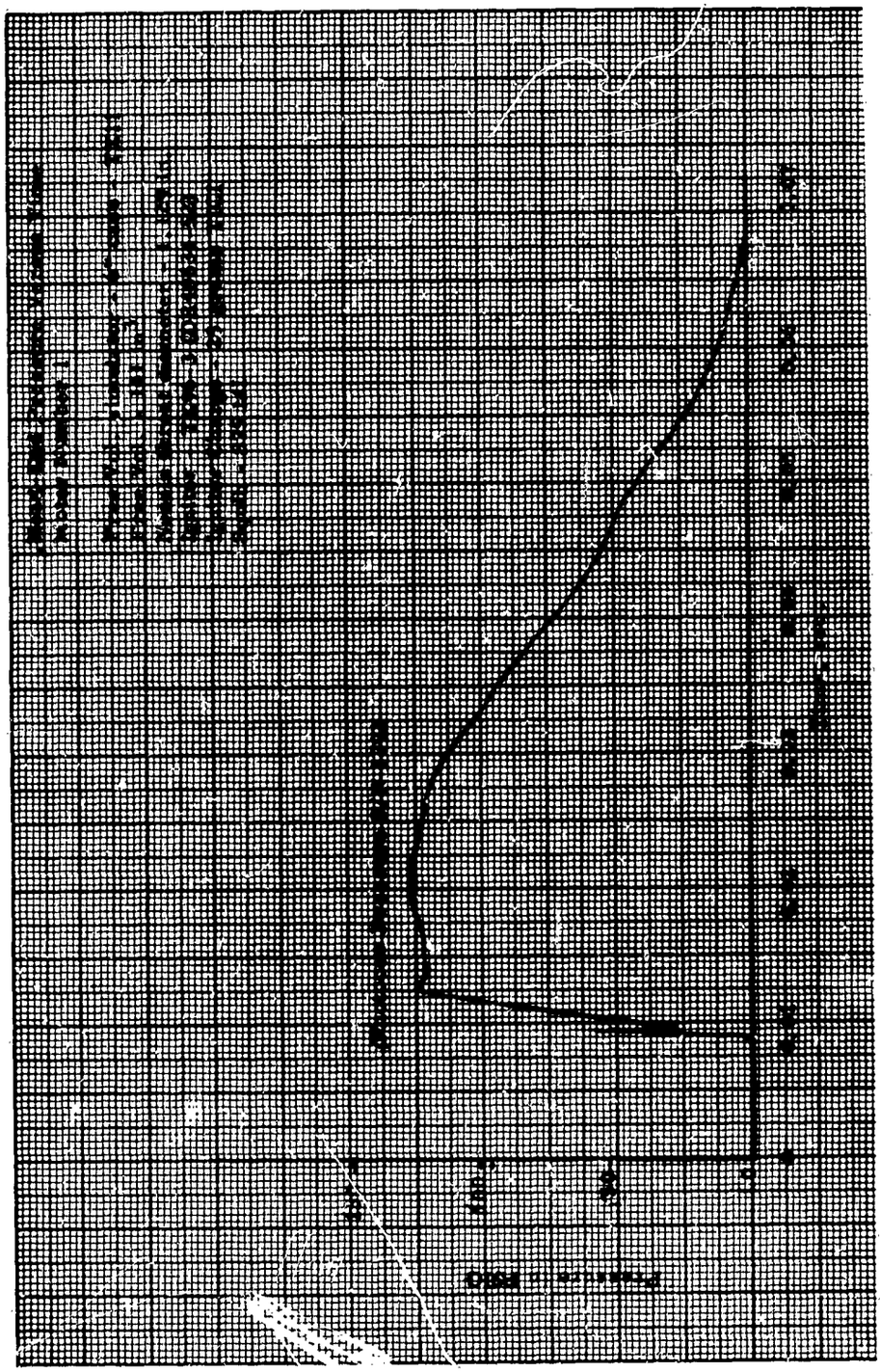


Figure 43. Igniter Pressure Versus Time Trace, TX11 Motor No. 1 (Empty)

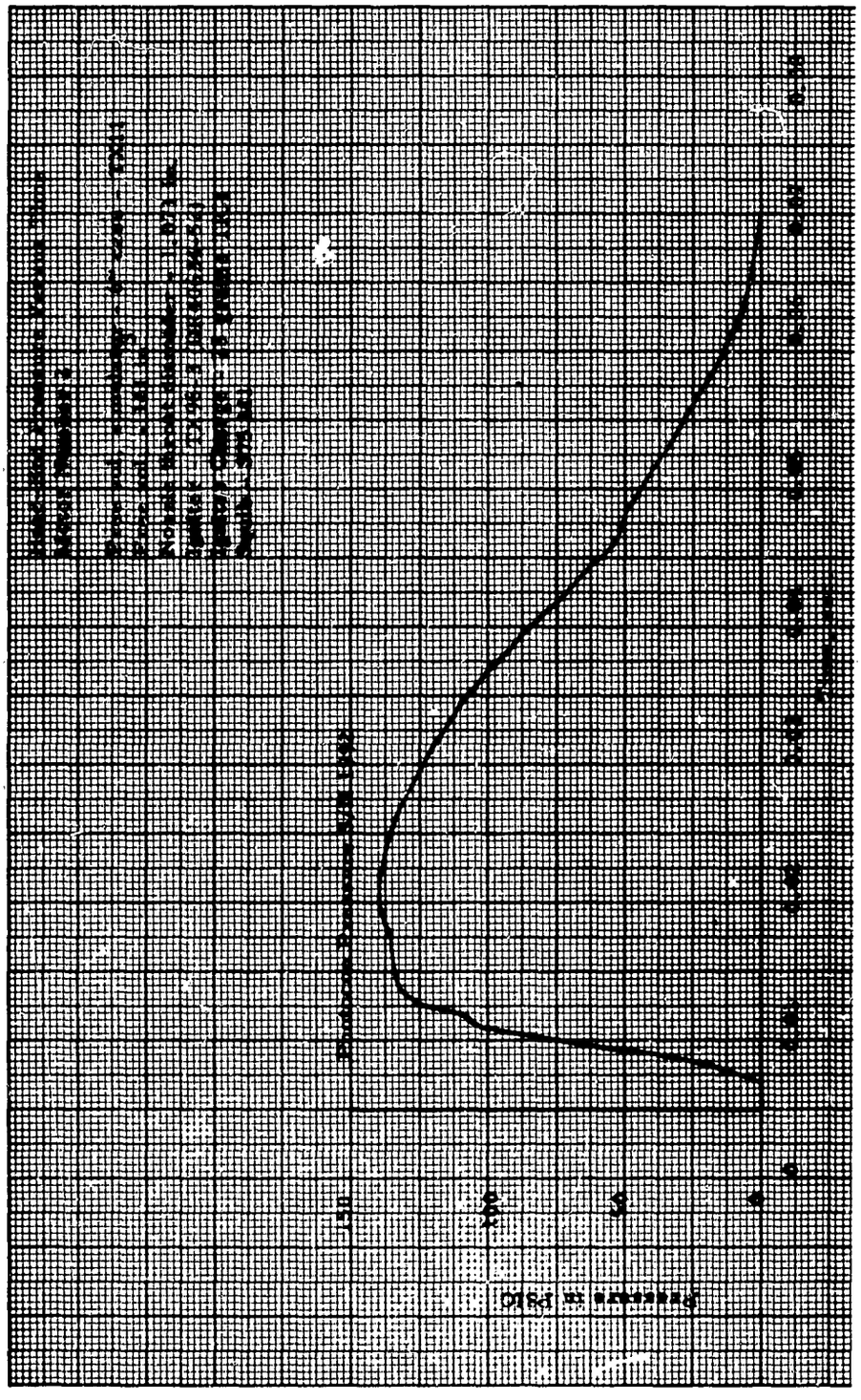


Figure 44. Igniter Pressure Versus Time Trace, TX11 Motor No. 2 (Empty)

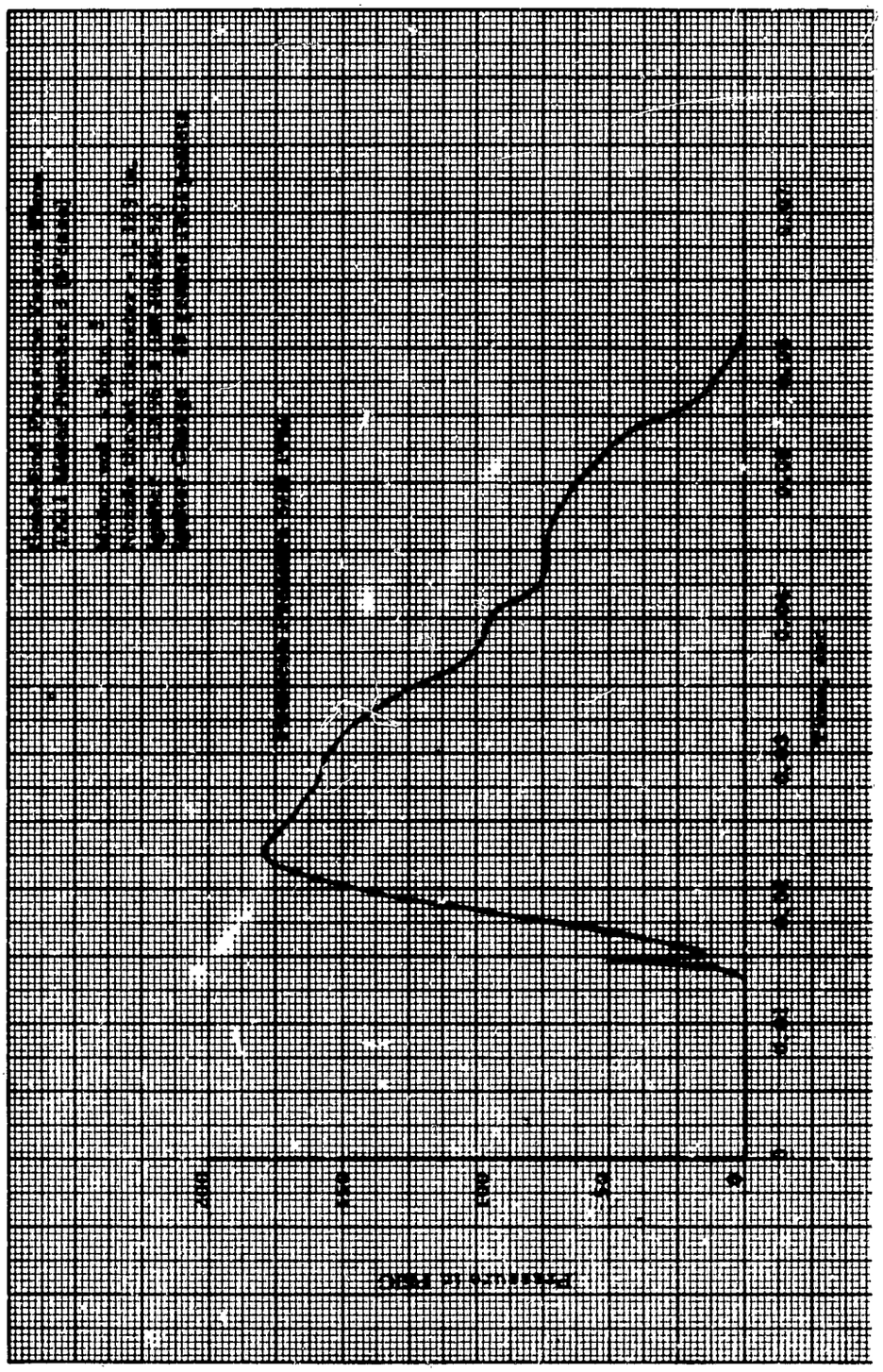


Figure 45. Attempted Ignition of Combustible Core, TX11 Motor No. 3

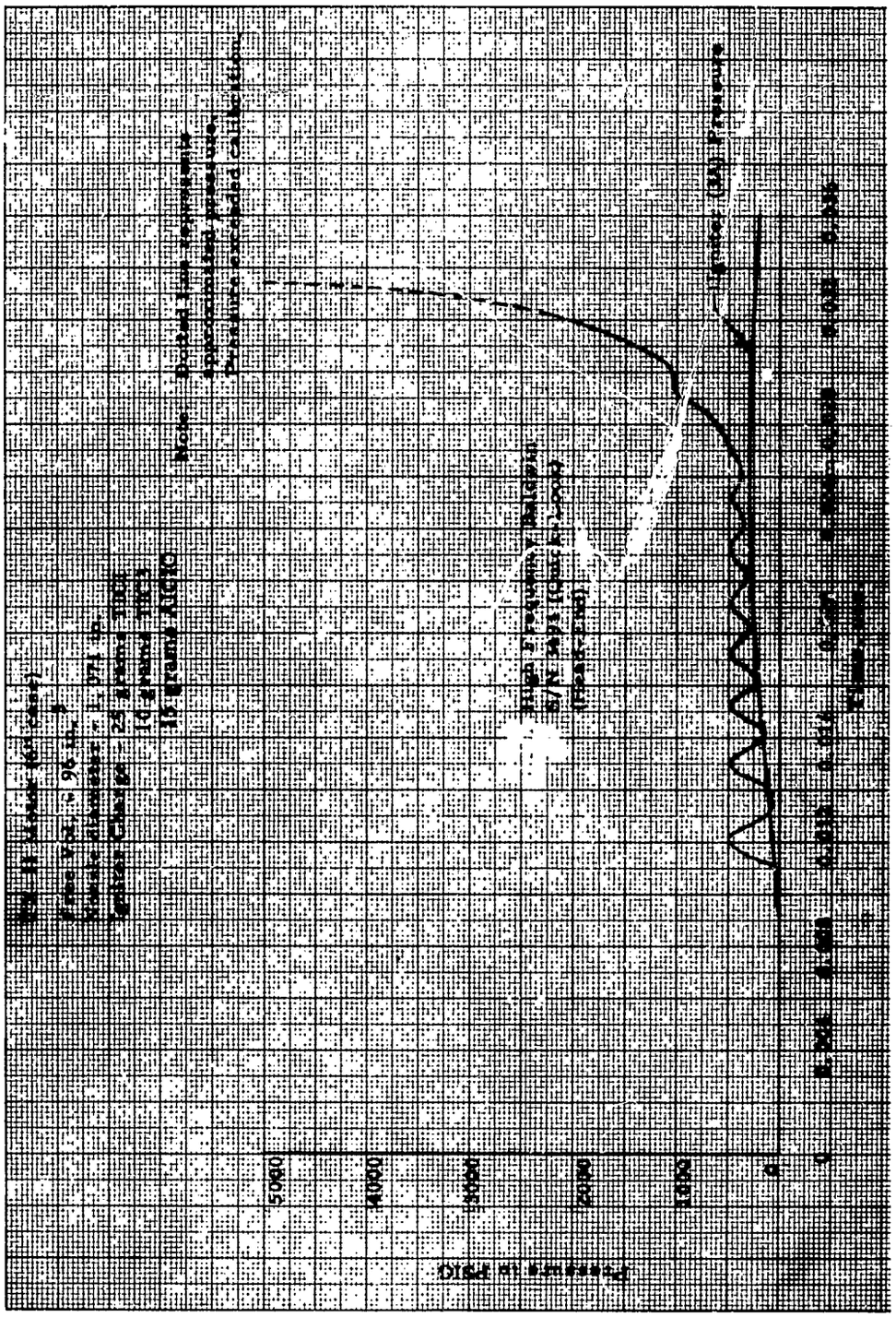


Figure 46. Pressure Versus Time Trace, Retest of Combustible Core Motor No. 3

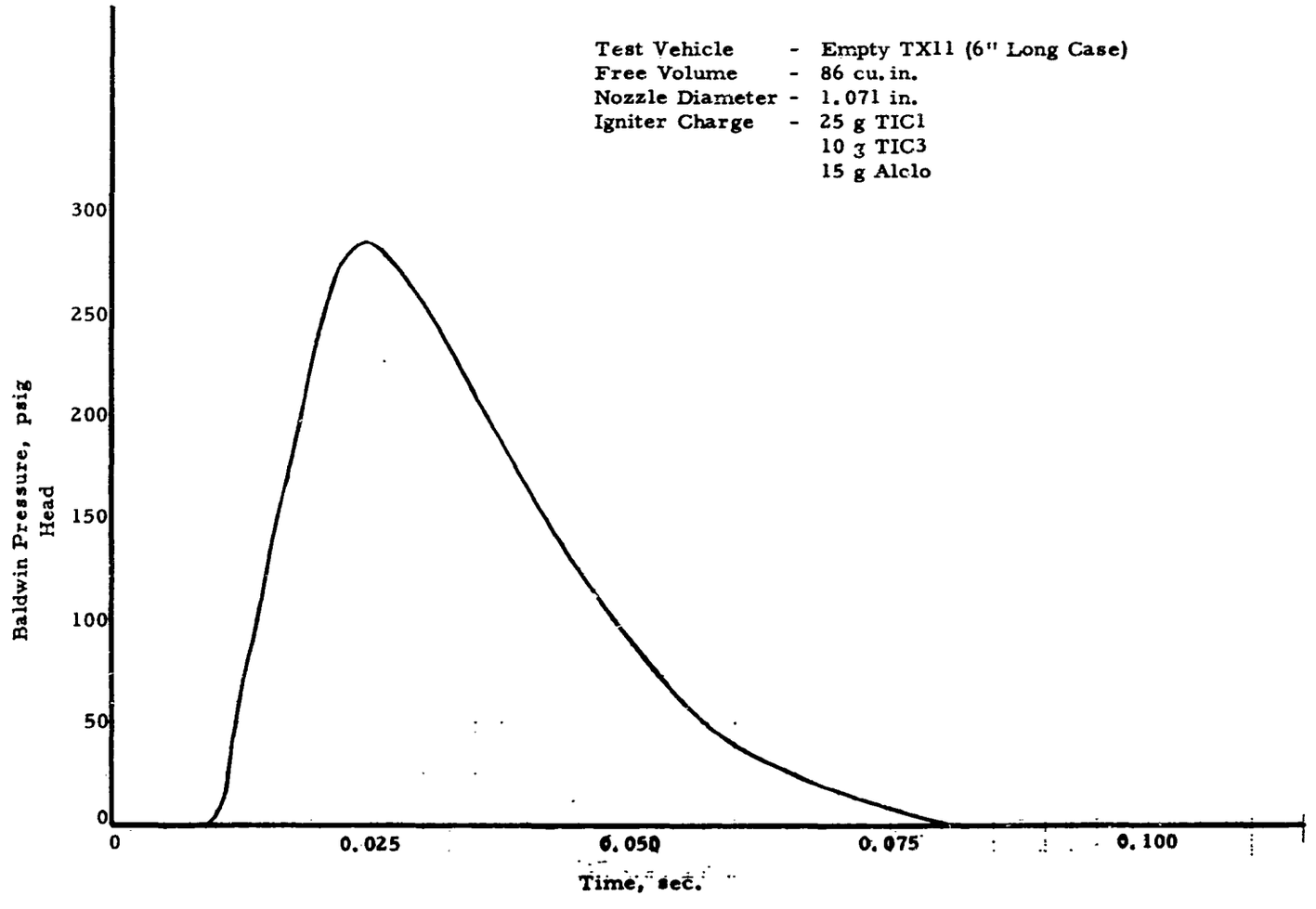


Figure 47. Igniter Pressure Versus Time Plot, Empty TX11 Motor

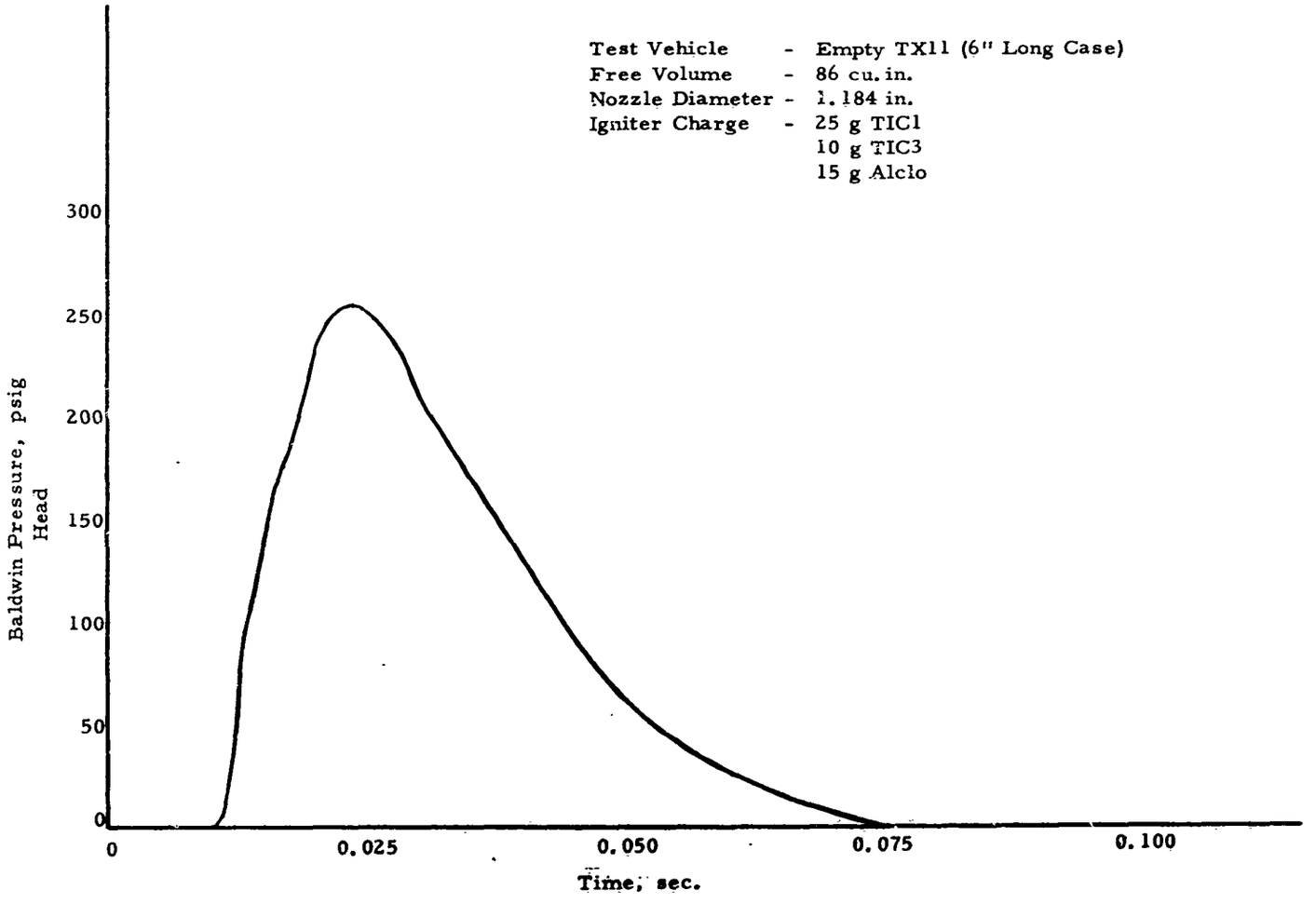


Figure 48. Igniter Pressure Versus Time Plot, Empty TX11 Motor

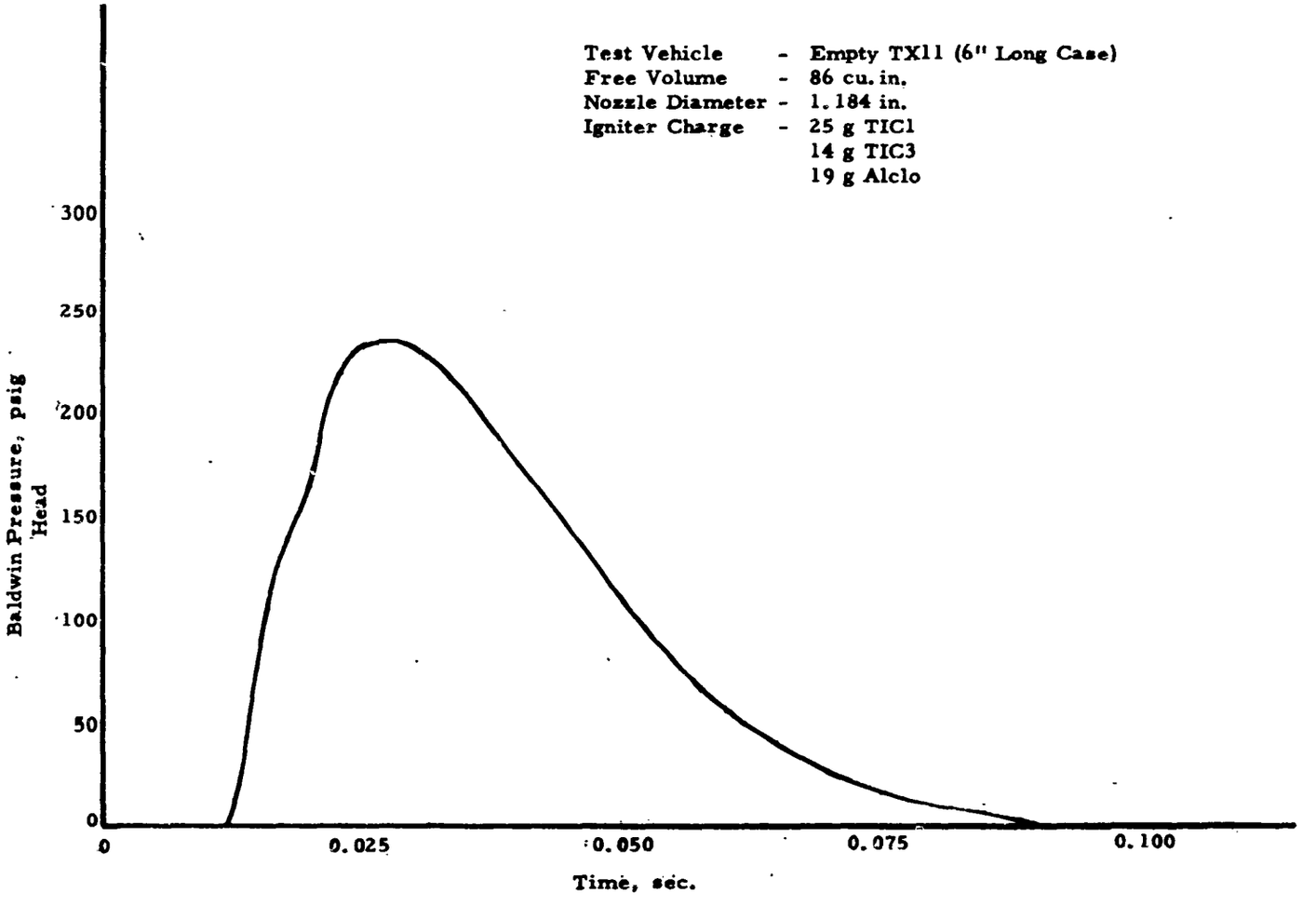


Figure 49. Igniter Pressure Versus Time Plot, Empty TX11 Motor

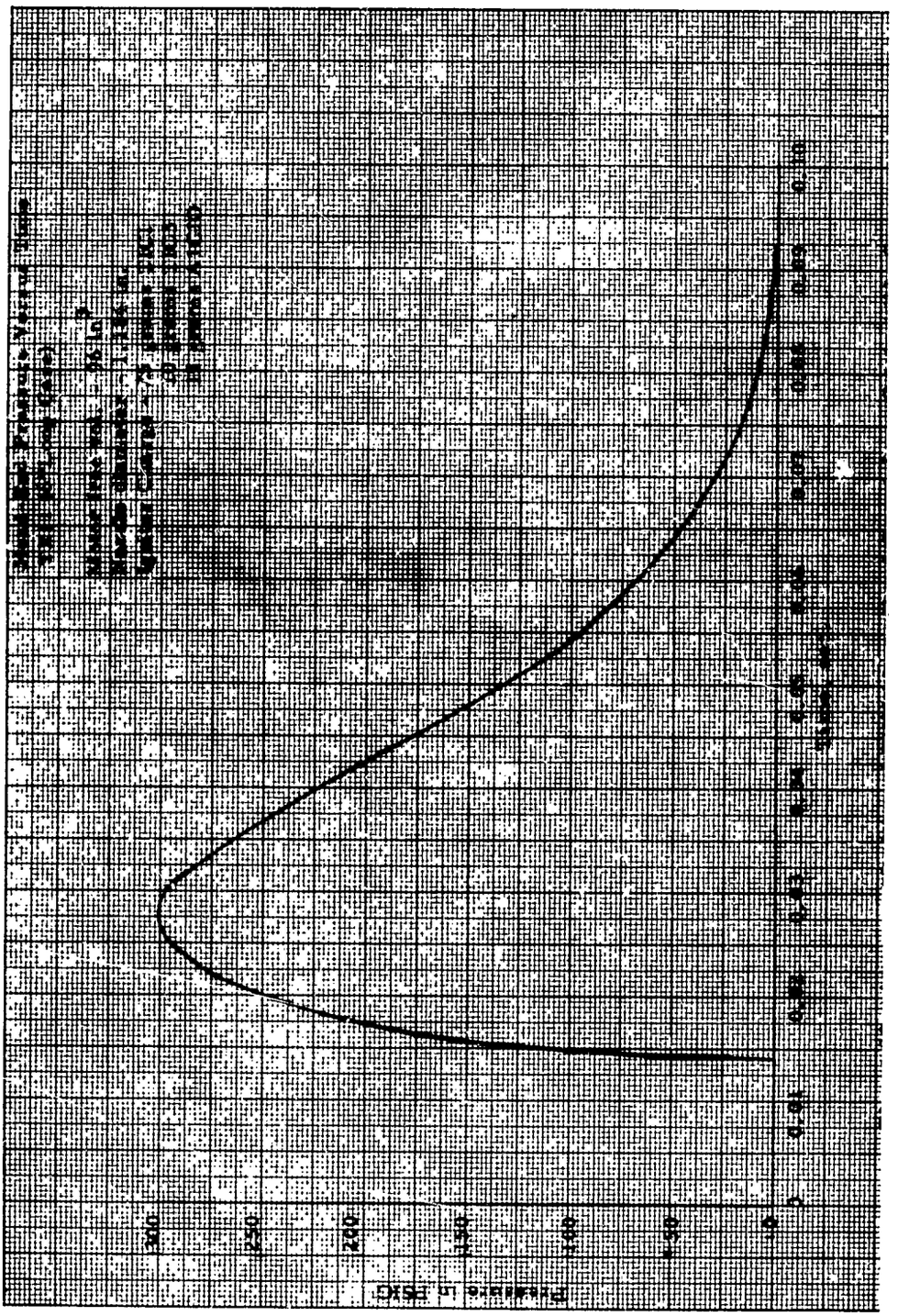


Figure 50. Attempted Ignition of TX11 Motor No. 4 Containing a Combustible Core

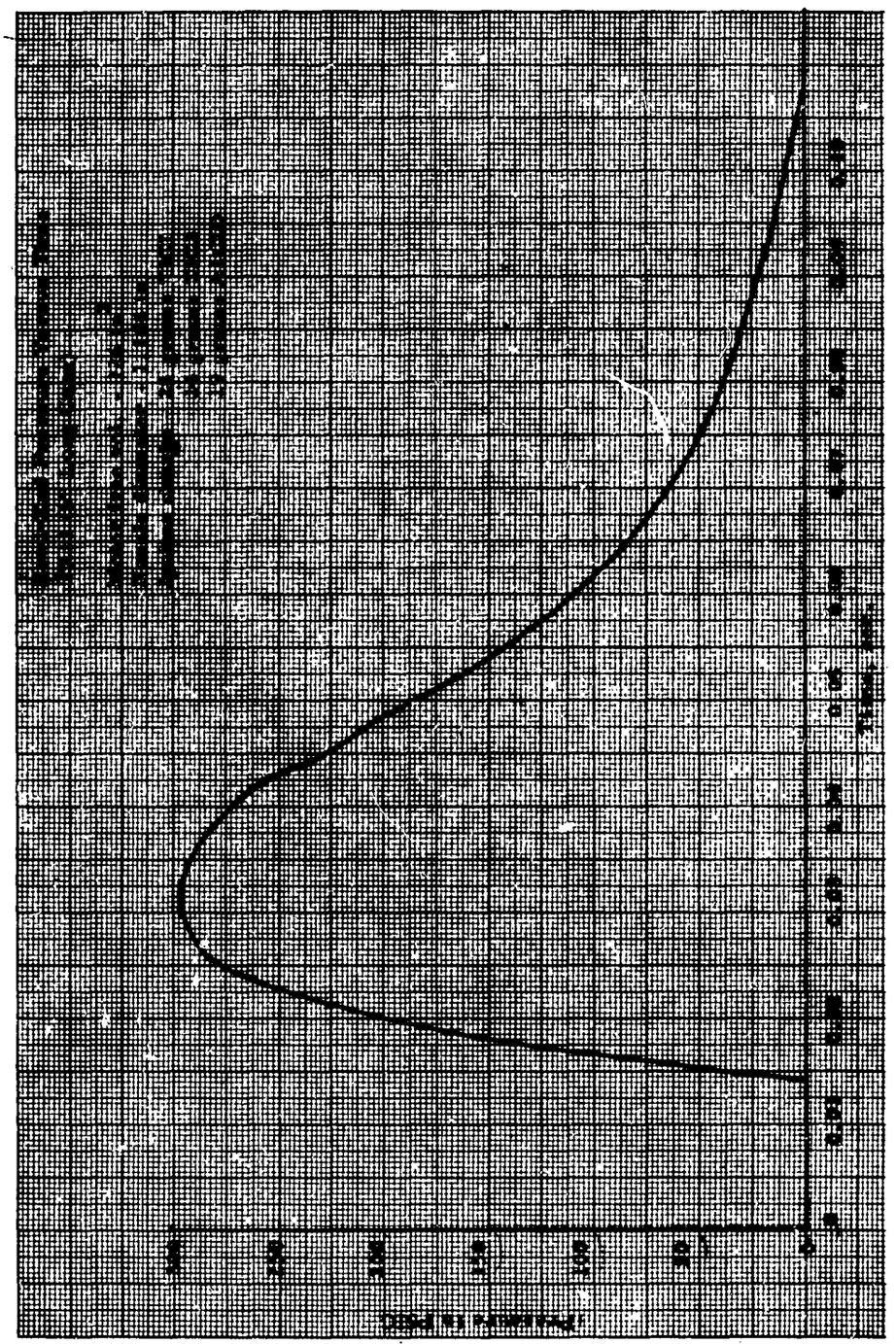


Figure 51. Igniter Pressure Versus Time Trace, Motor No. 4

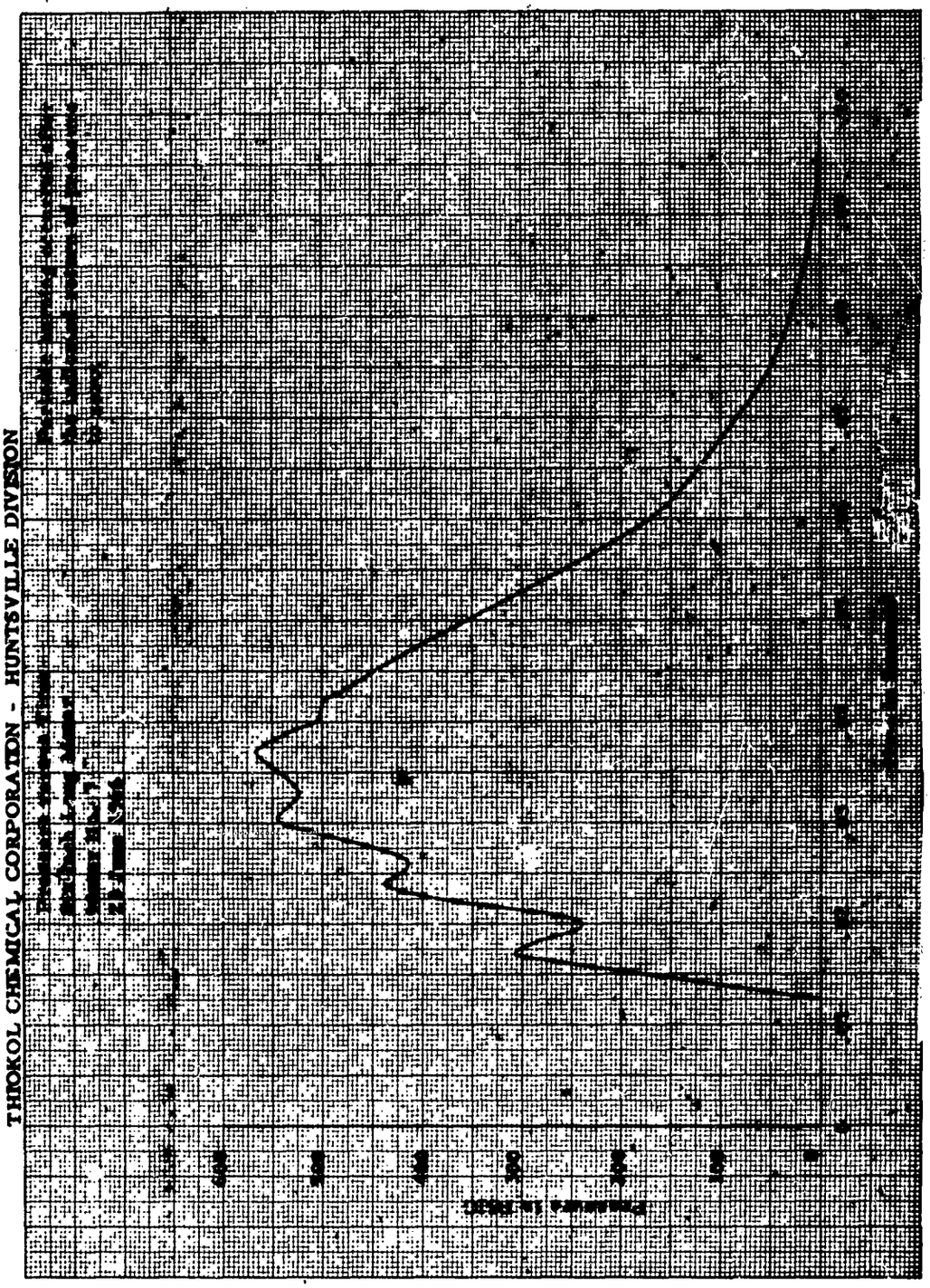


Figure 52. Pressure Versus Time Trace, Motor No. 7

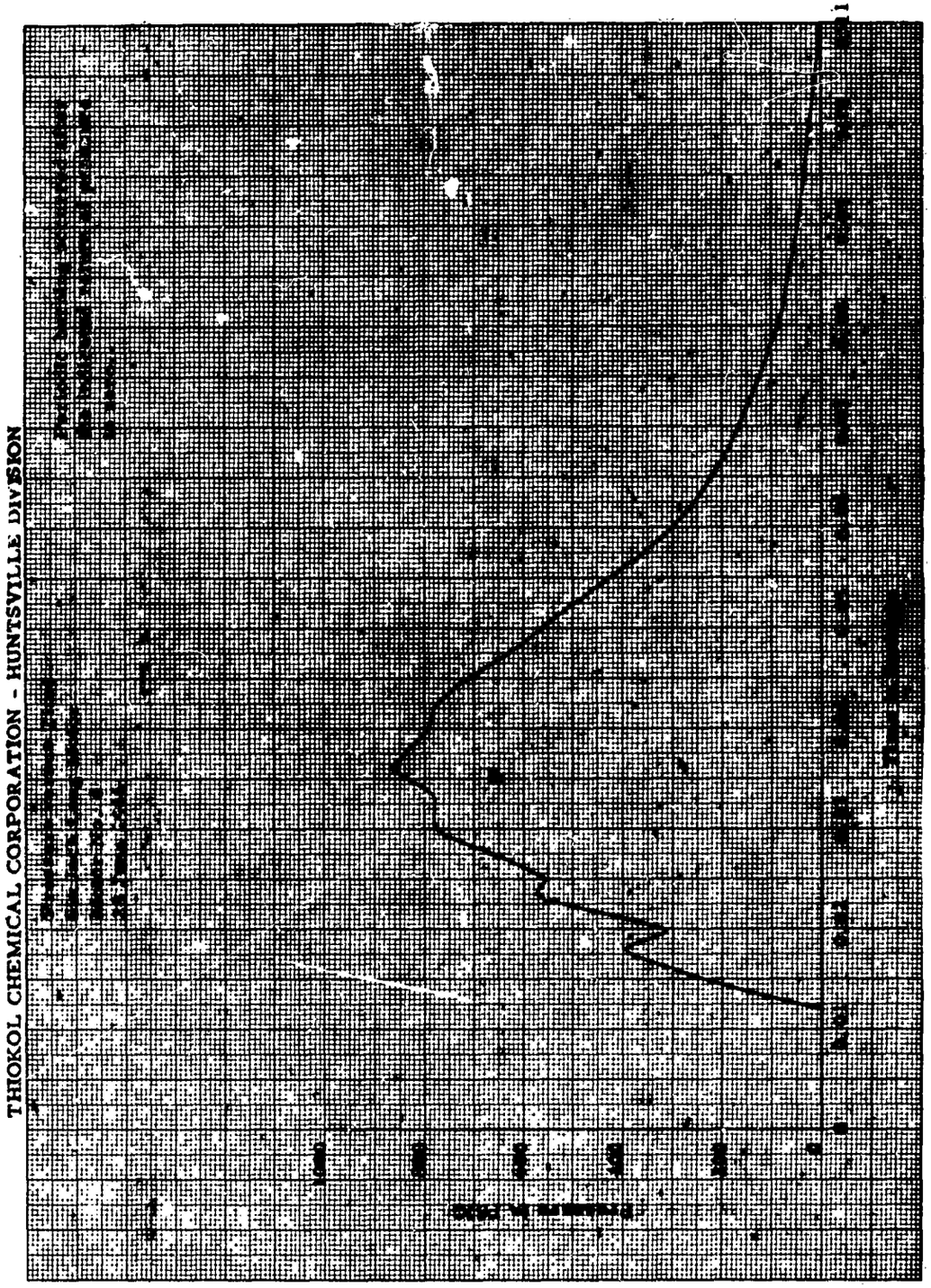


Figure 53. Pressure Versus Time Trace, Motor No. 8

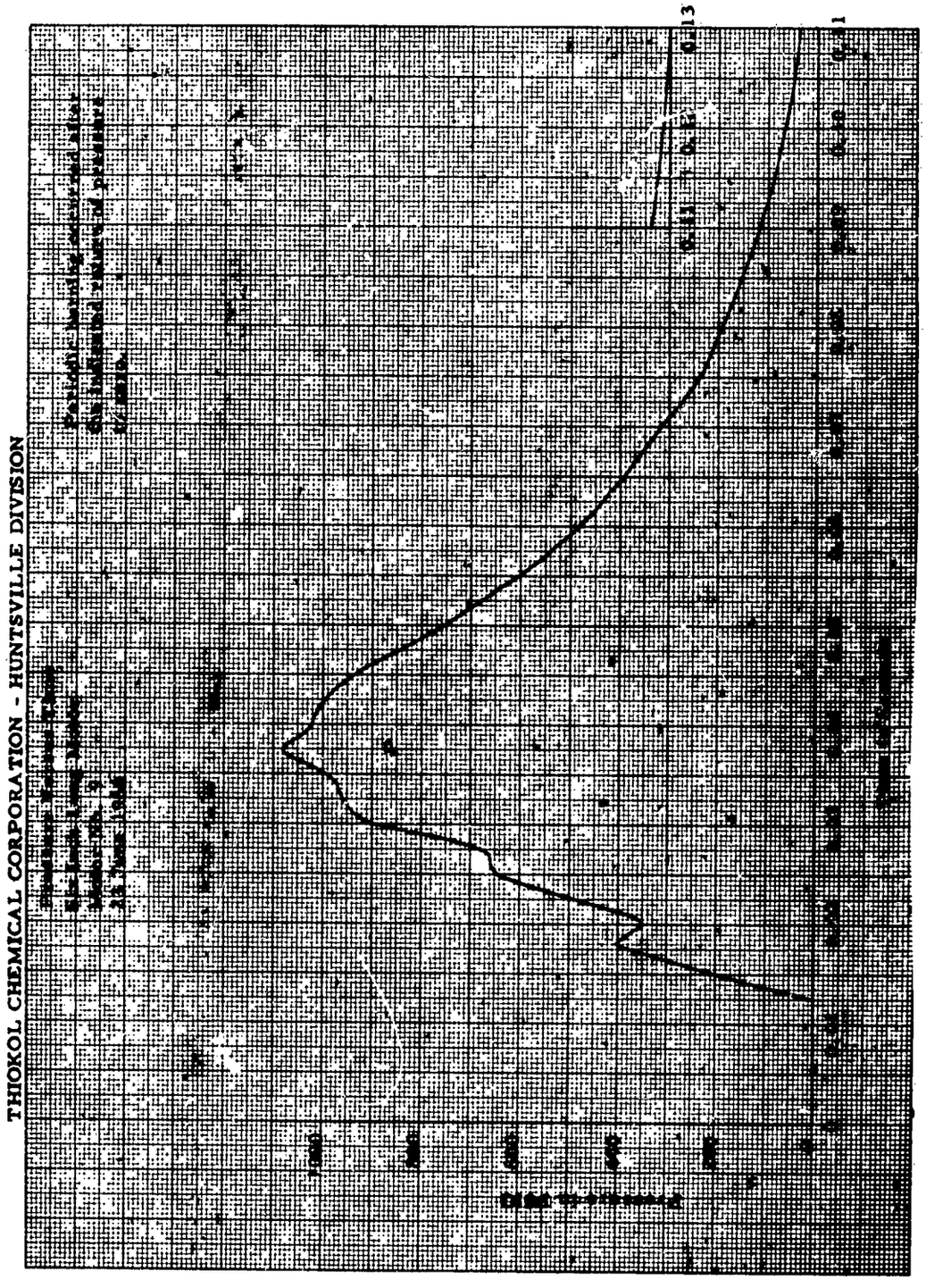


Figure 54. Pressure Versus Time Trace, Motor No. 9

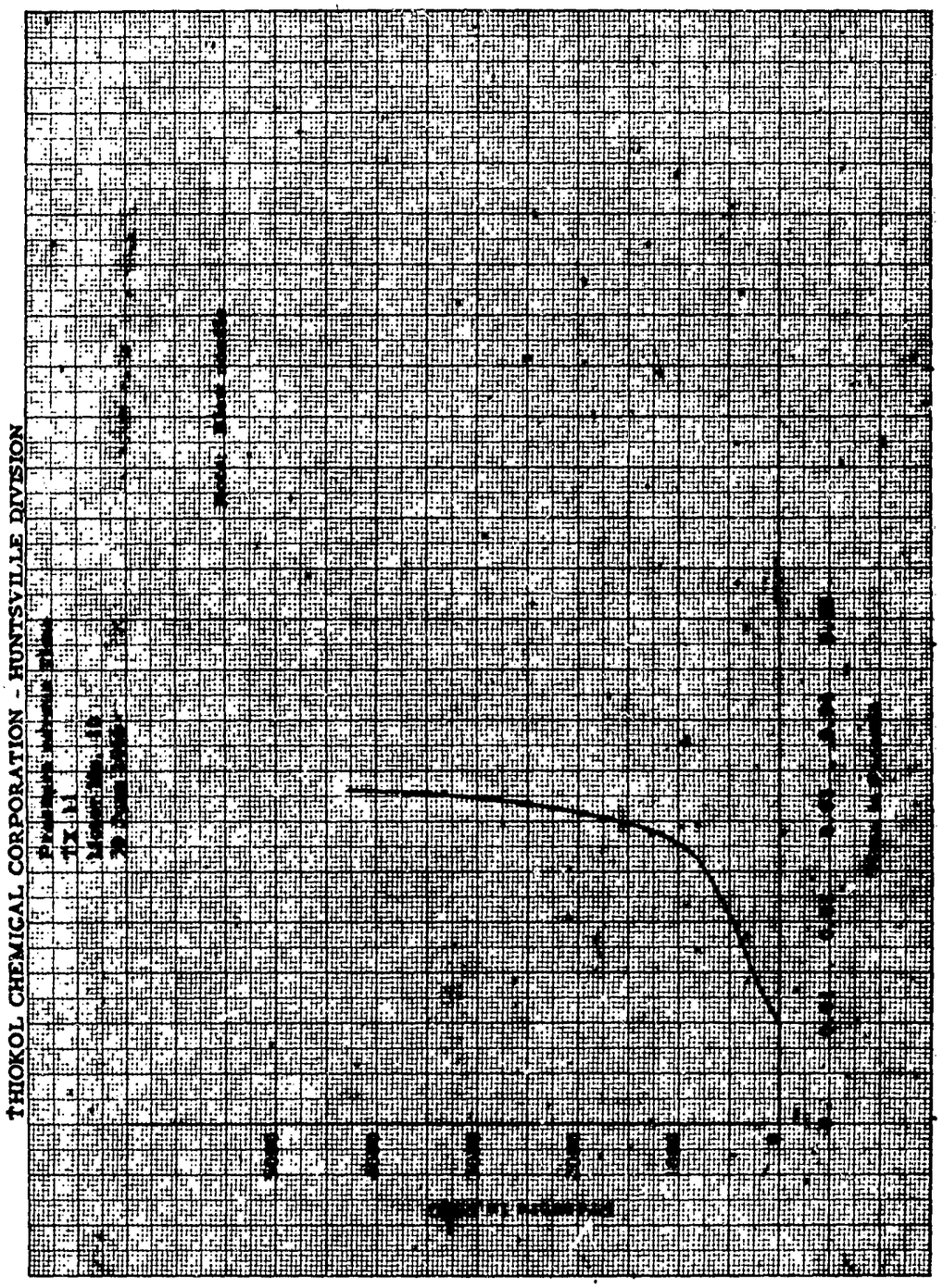


Figure 55. Pressure Versus Time Trace, Motor No. 10

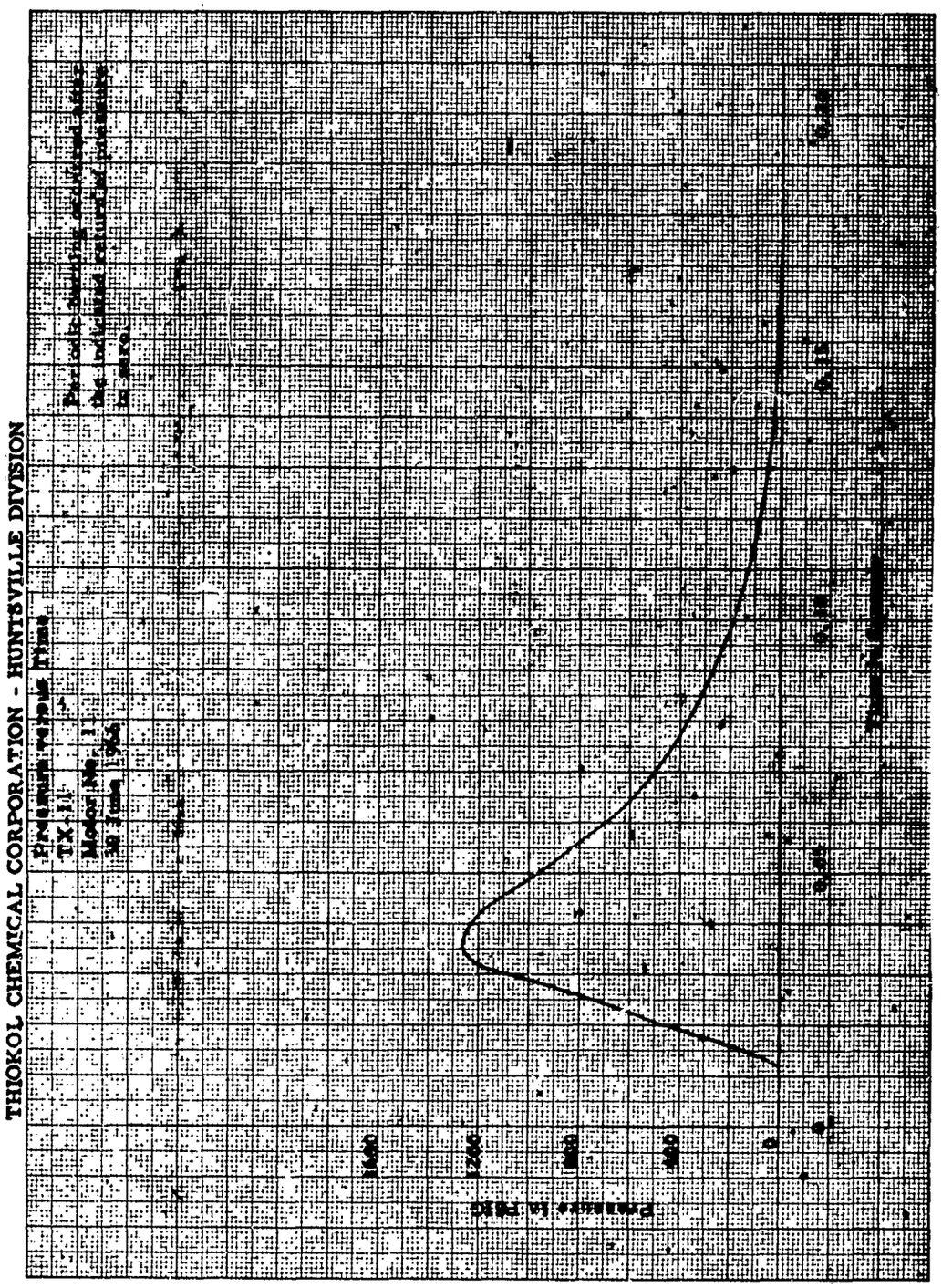


Figure 56. Pressure Versus Time Trace, Motor No. 11

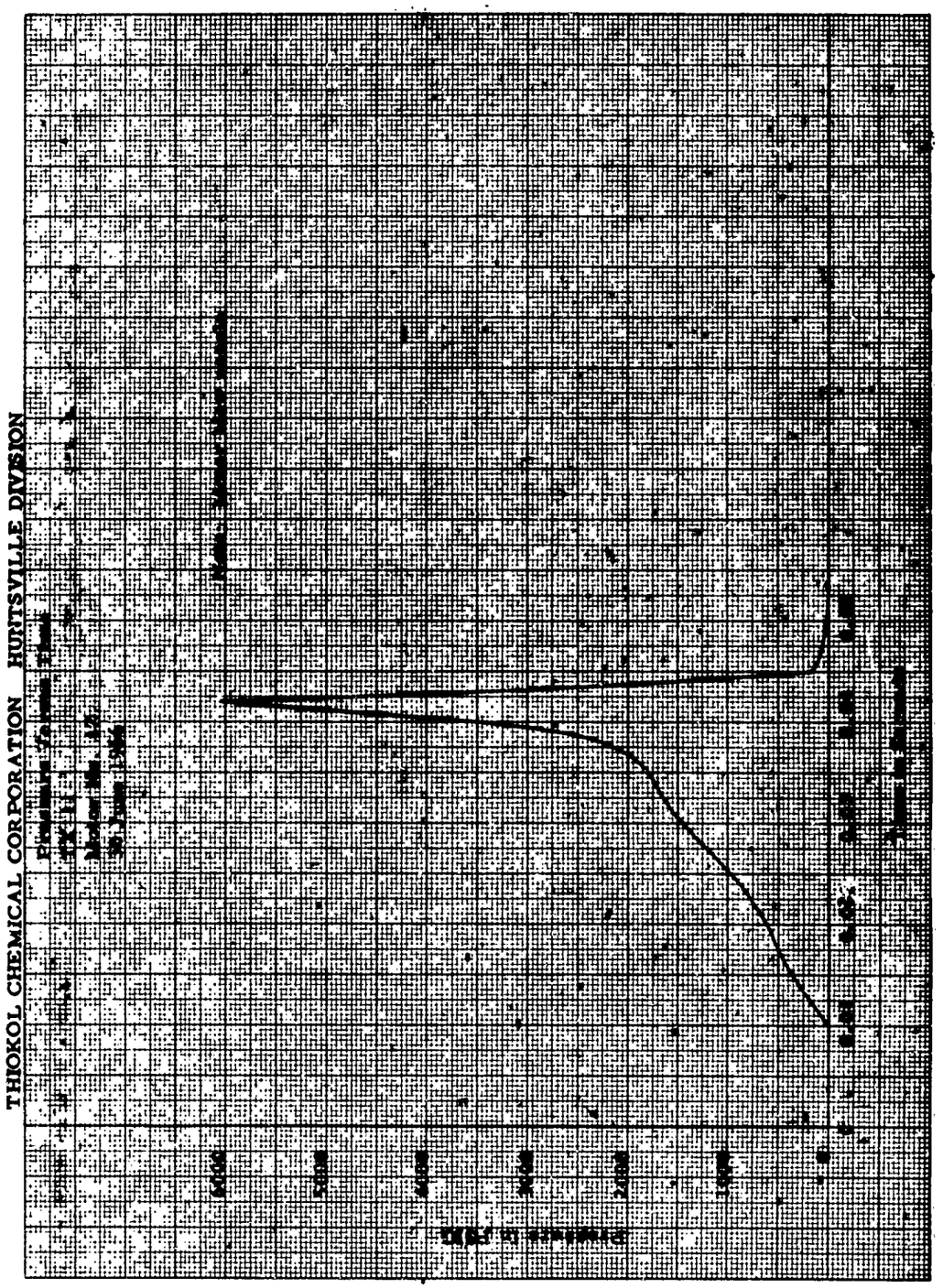


Figure 57. Pressure Versus Time Trace, Motor No. 12

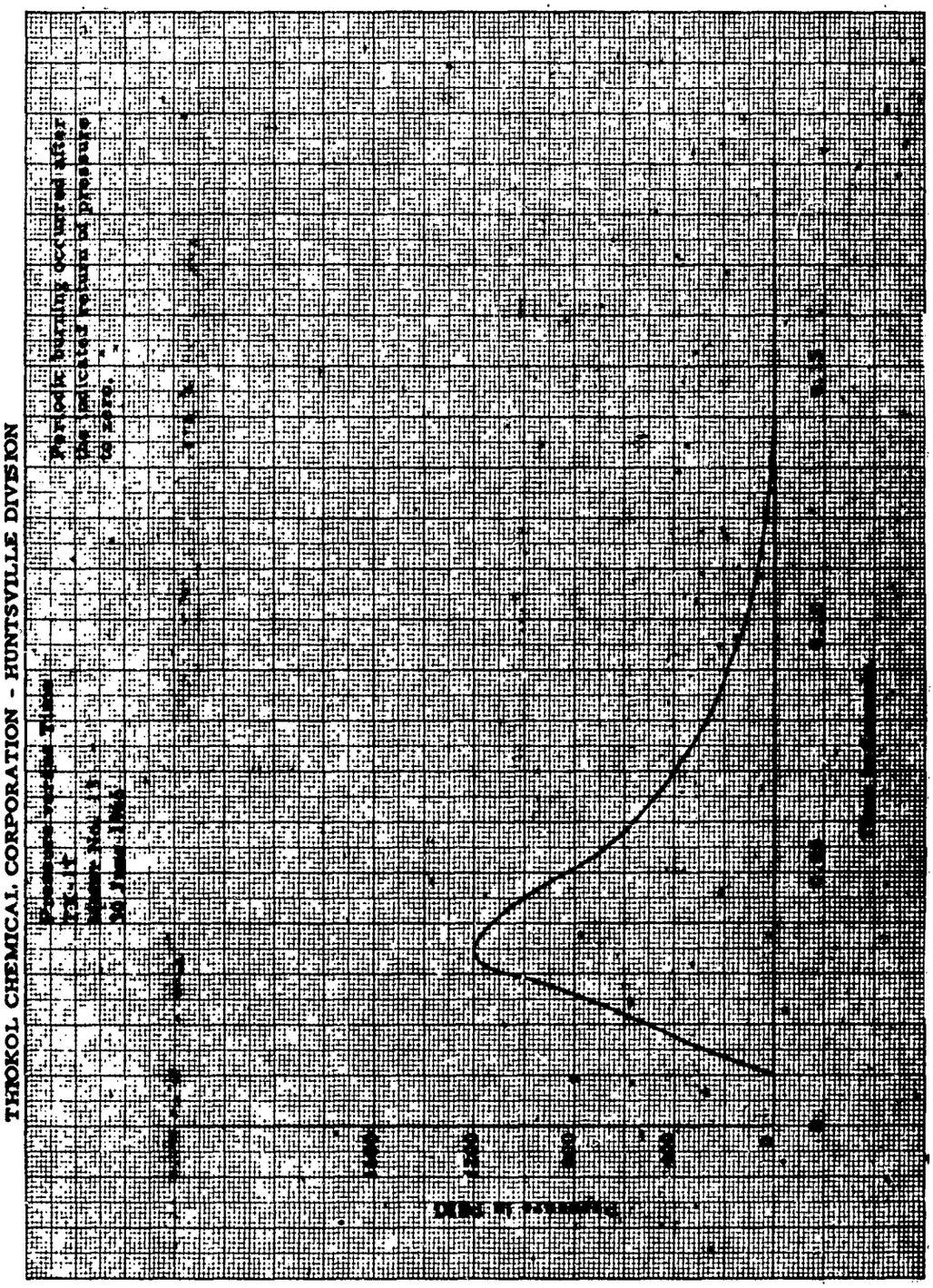


Figure 58. Pressure Versus Time Trace, Motor No. 13

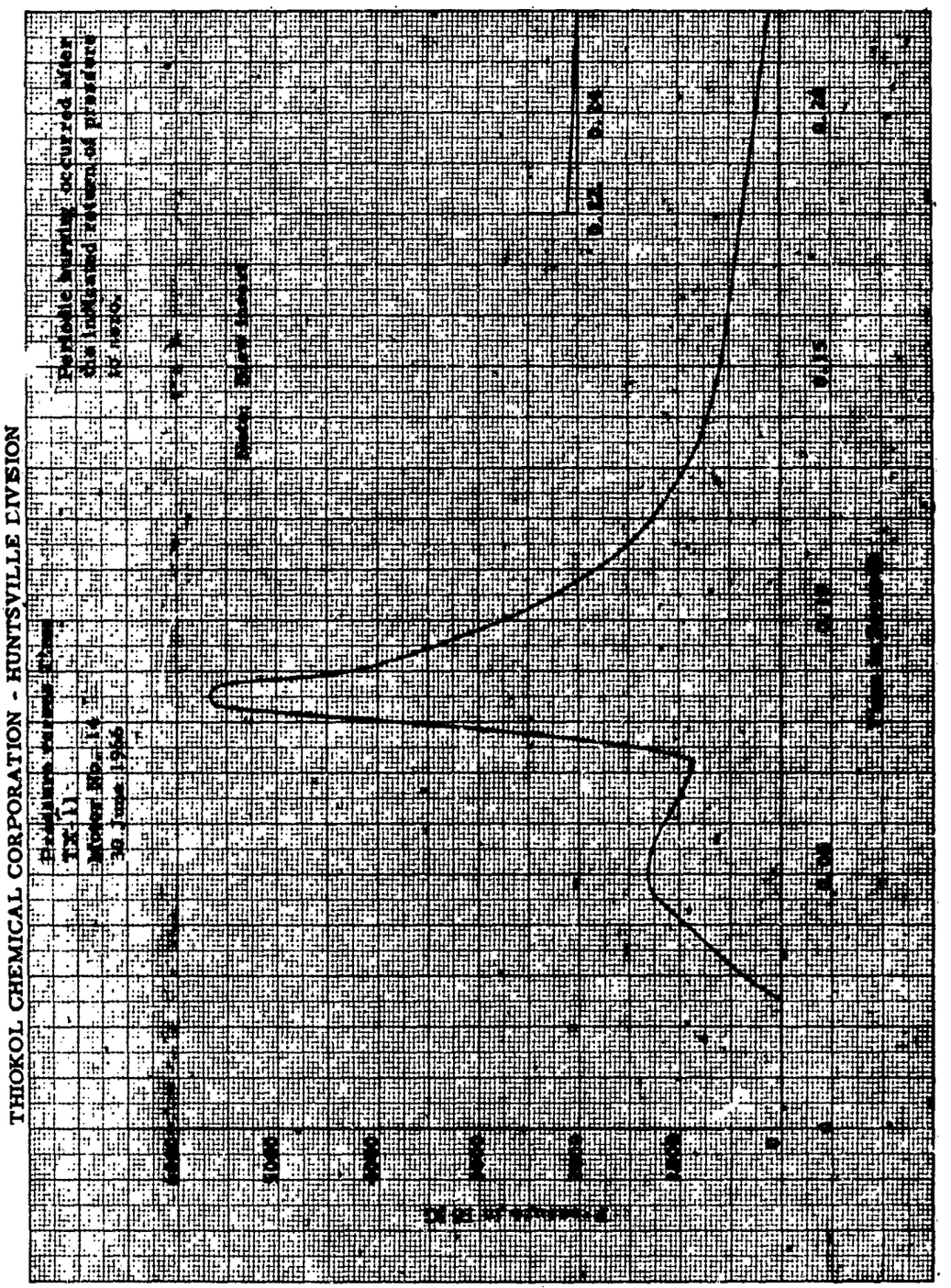


Figure 59. Pressure Versus Time Trace, Motor No. 14

Figure 60. Photograph Showing Residue after Firing Motor No. 5

Figure 61. Photograph Showing Residue after Firing Motor No. 6

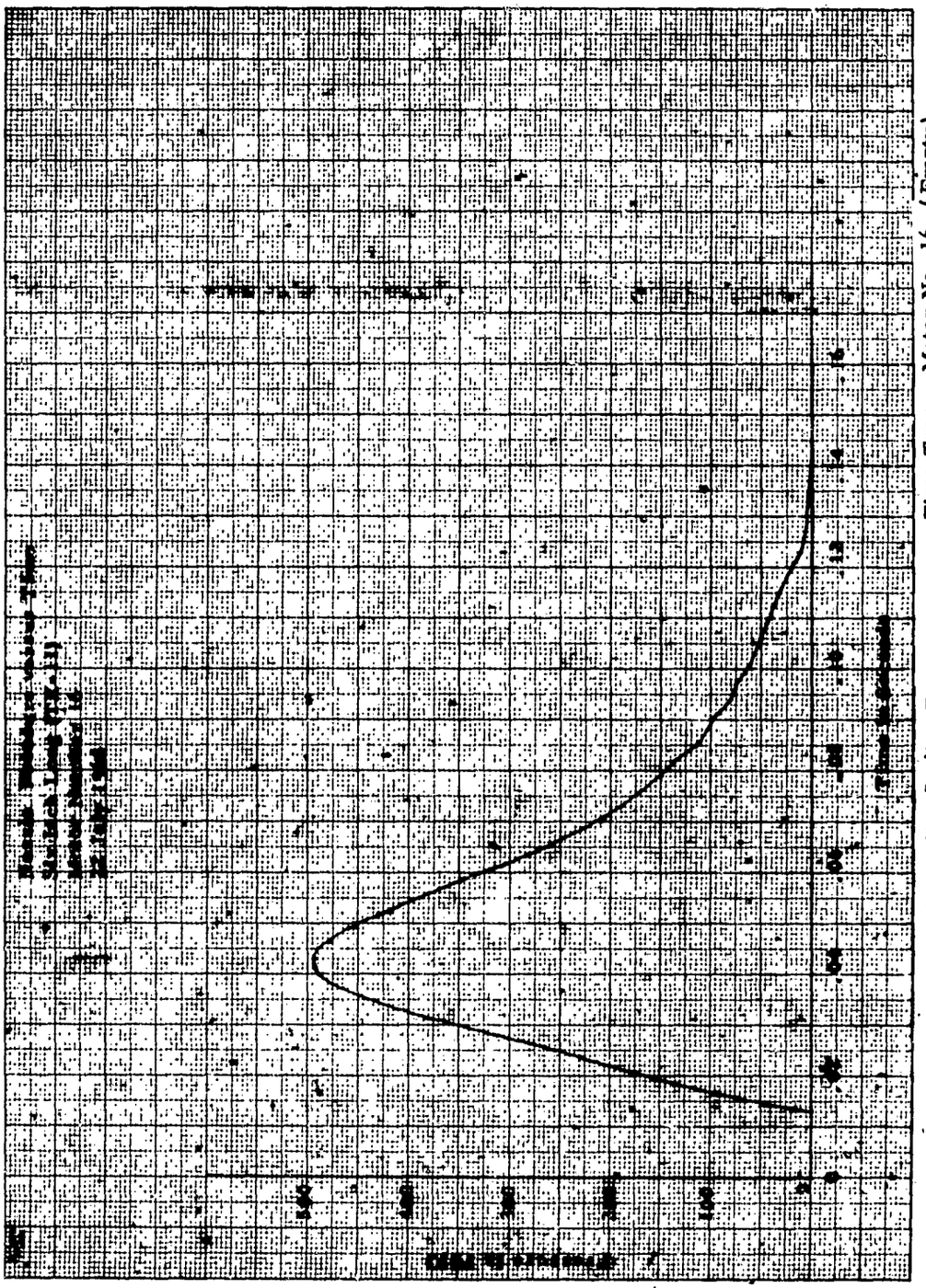


Figure 62. Igniter Pressure versus Time Trace, Motor No. 16. (Empty)

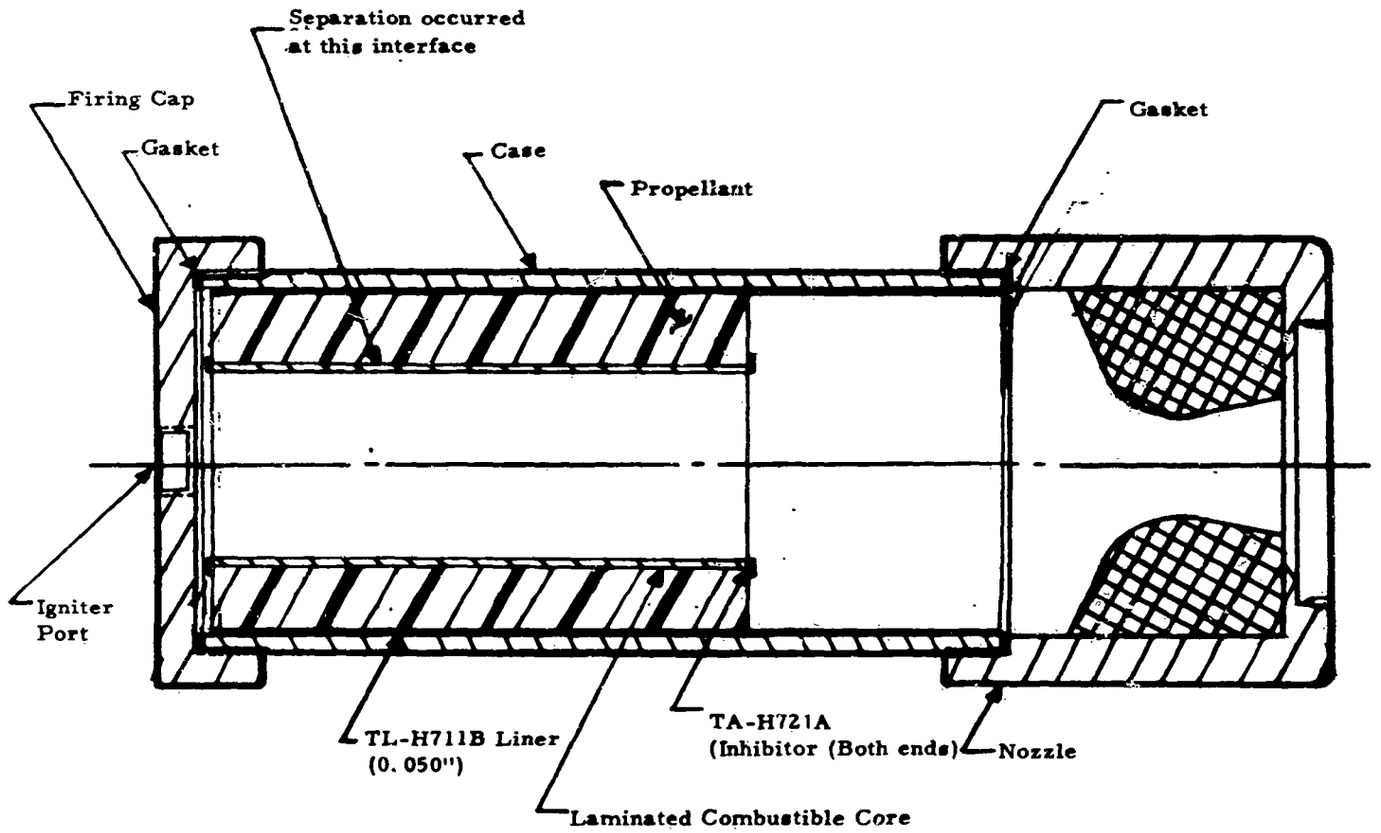


Figure 63. TX11 Motor (12-inch Case Length) Laminated Core and Propellant Configuration

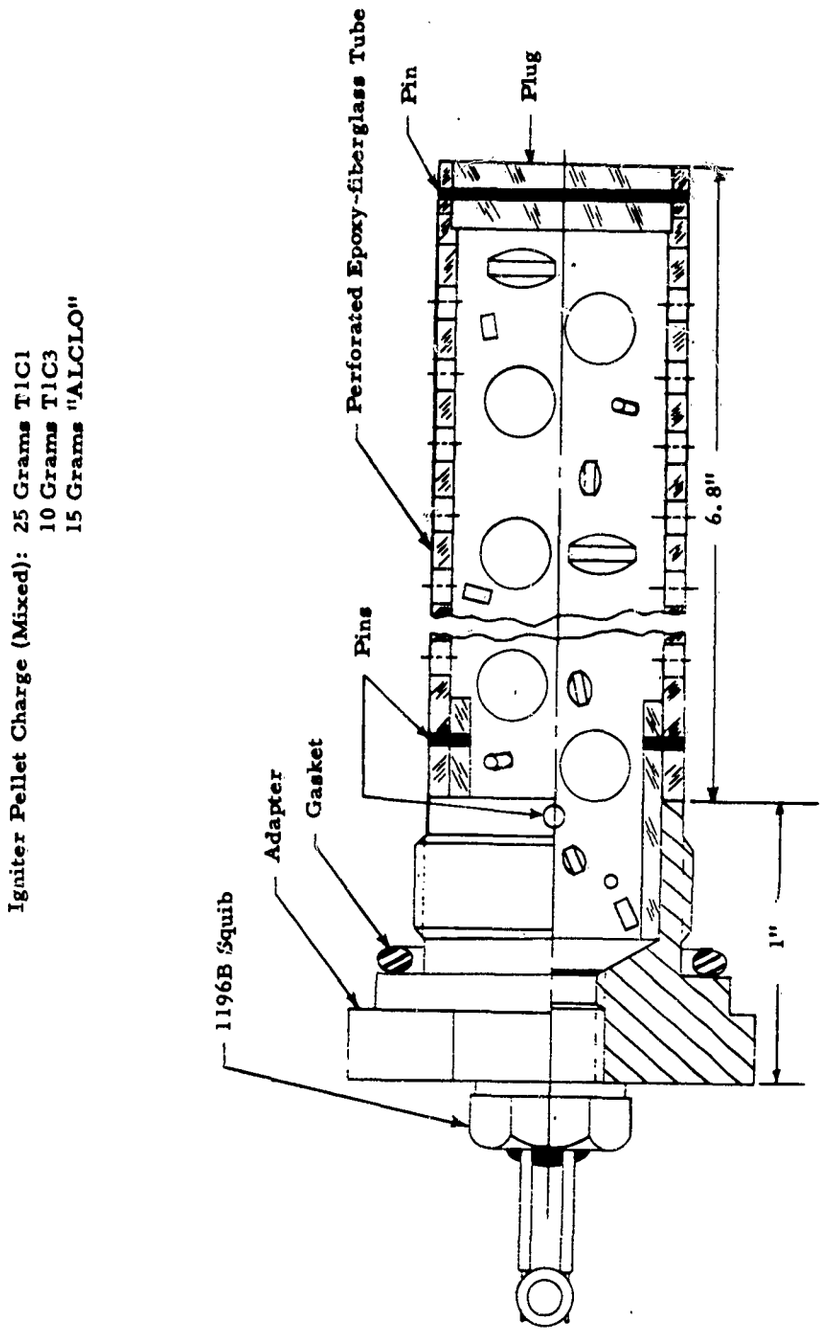


Figure 64. Modified TX96 Igniter for Combustible Core Test Motors.

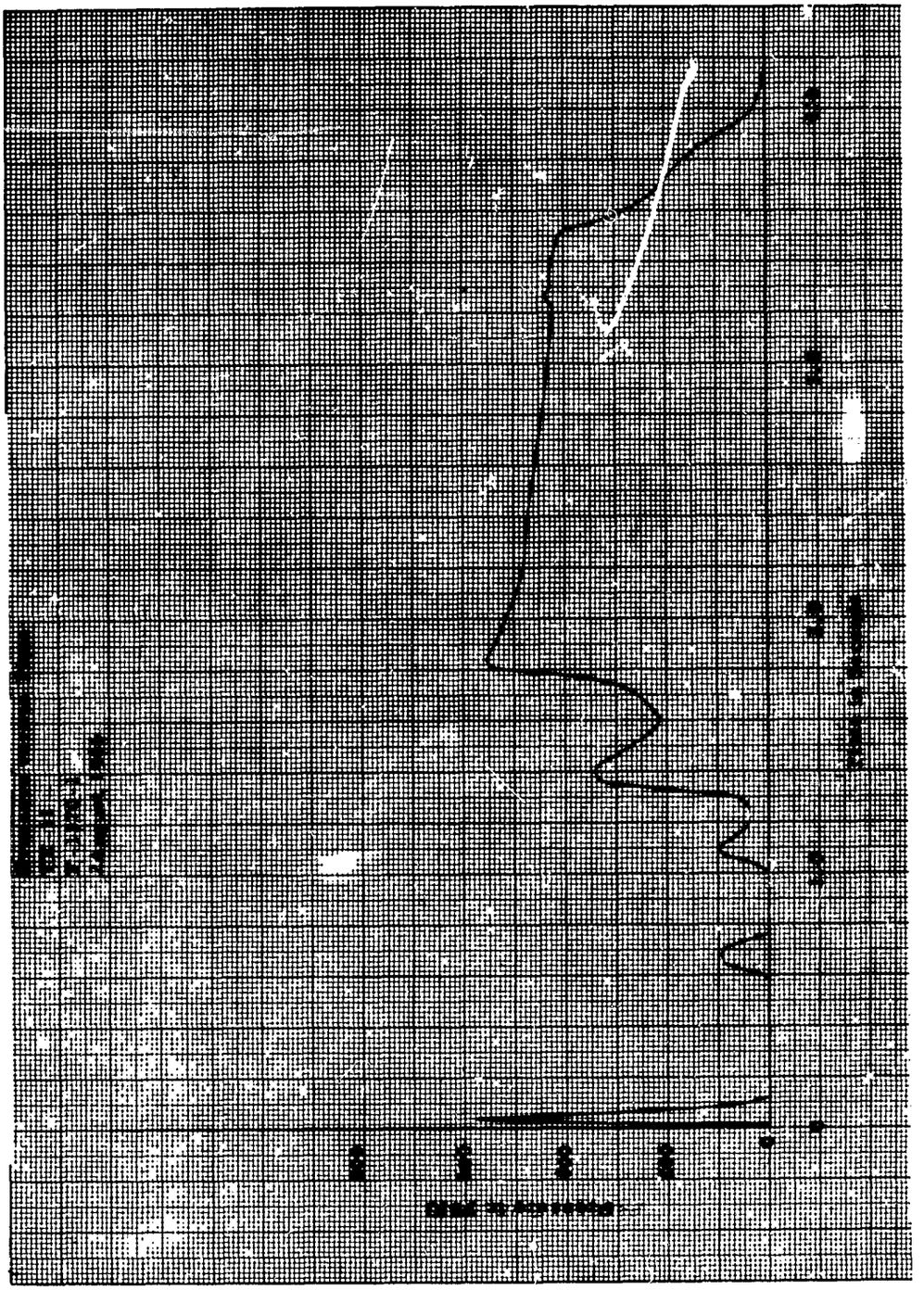


Figure 65. Pressure Versus Time Trace, Sub-scale TX11 Motor No. 1

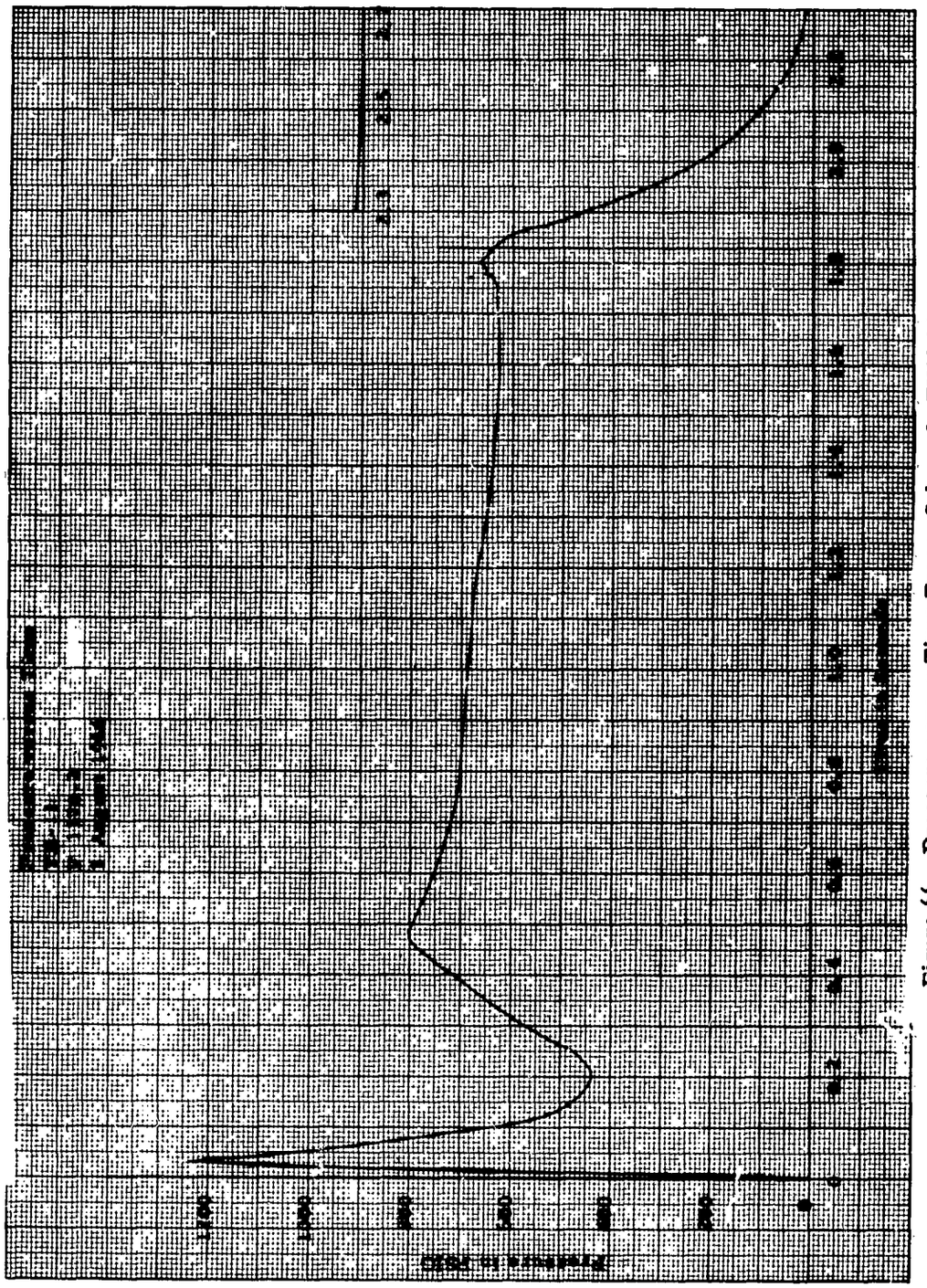


Figure 66. Pressure versus Time Trace, Sub-scale TX11 Motor No. 2.

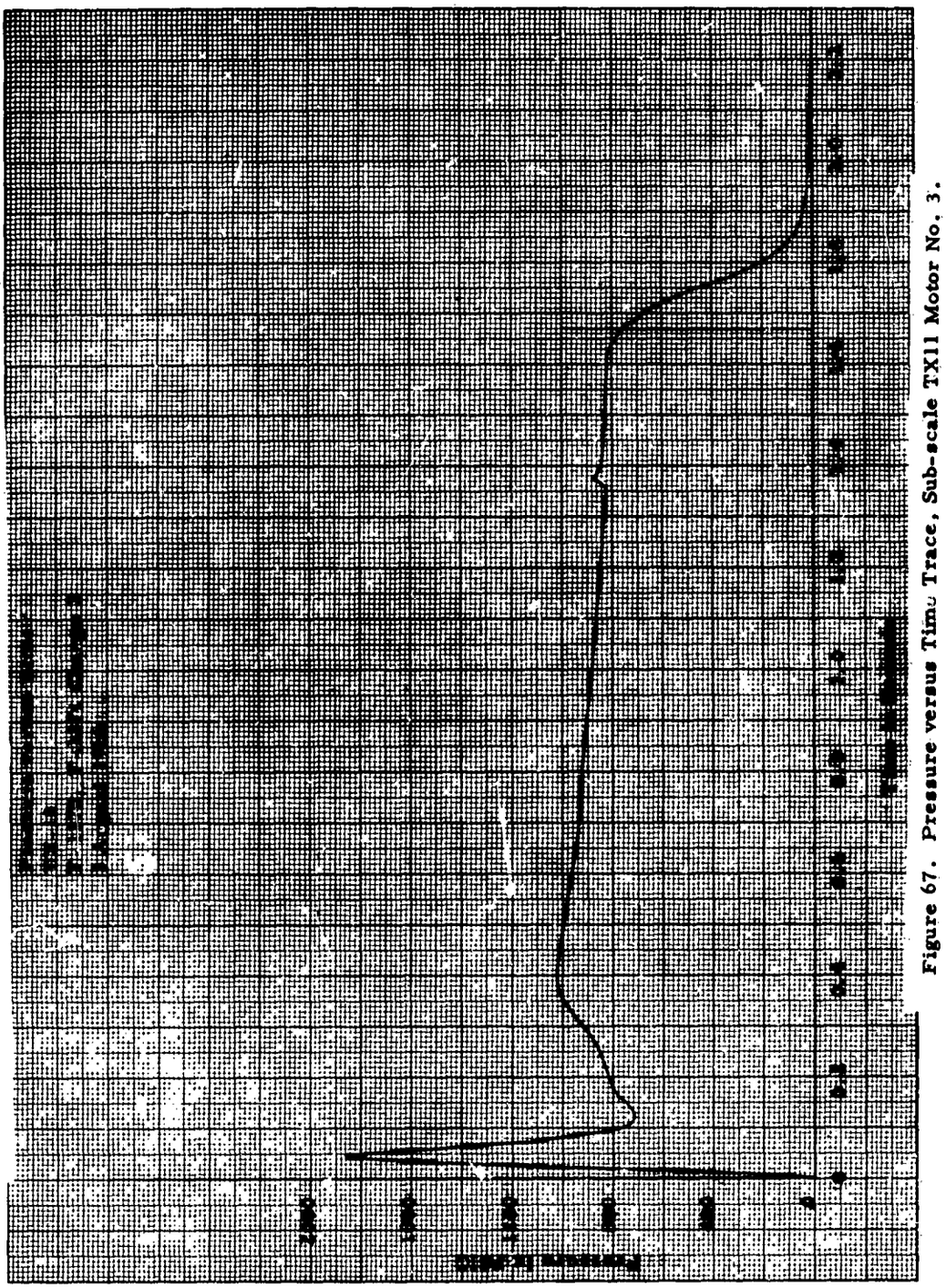


Figure 67. Pressure versus Time Trace, Sub-scale TX11 Motor No. 3.

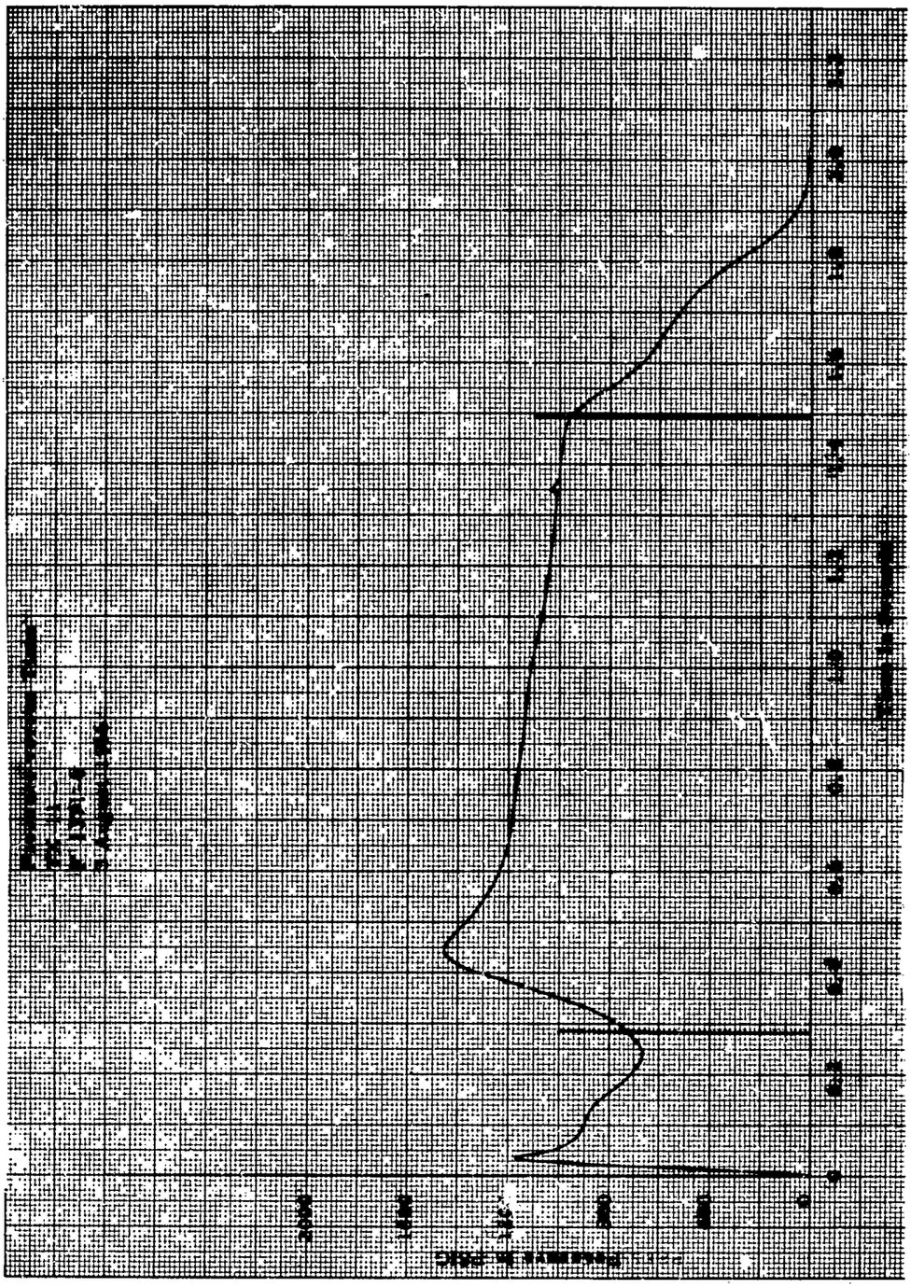


Figure 68. Pressure Versus Time Trace, Sub-scale TX11 Motor No. 4

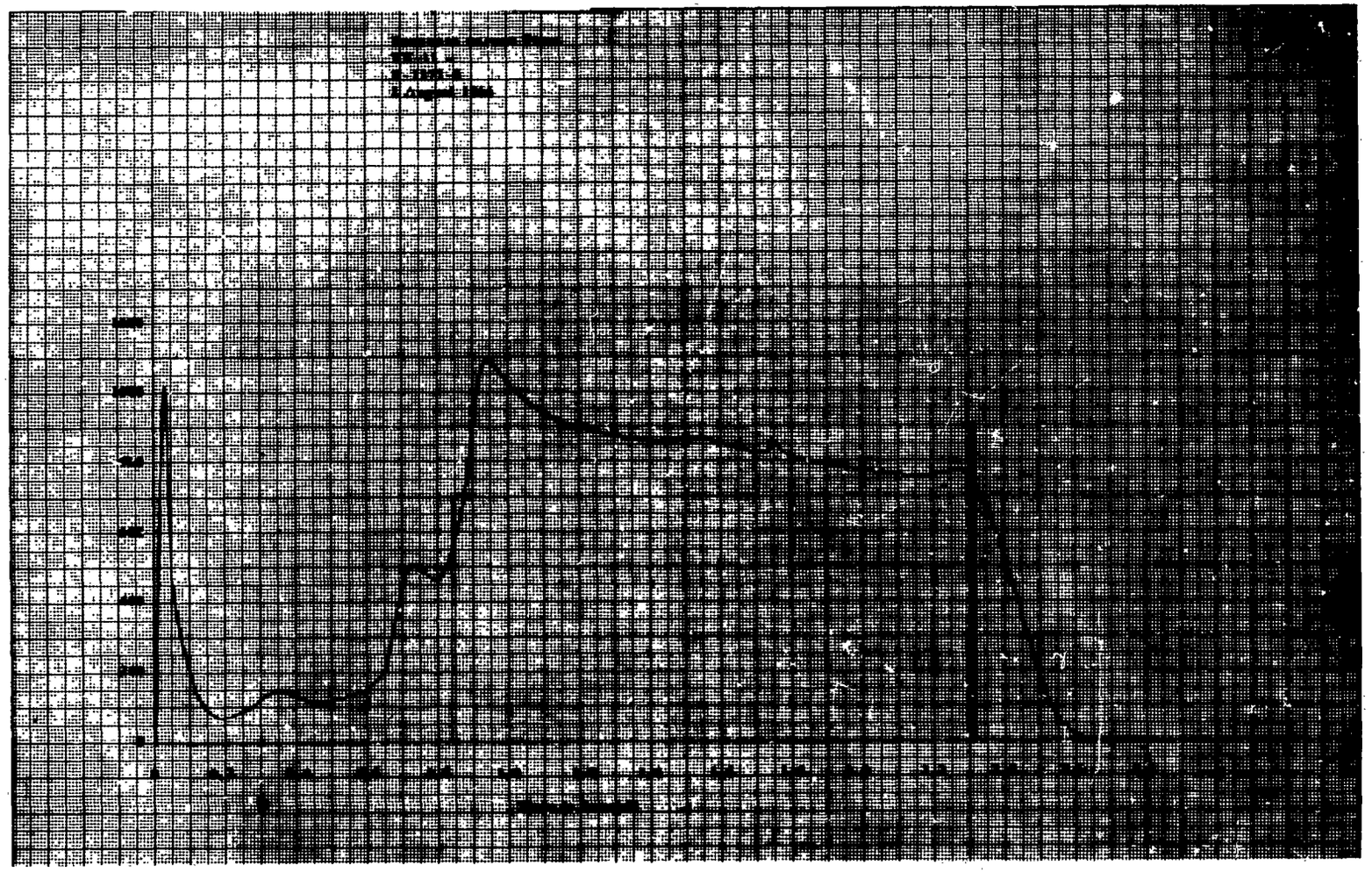


Figure 69. Pressure Versus Time Trace, Sub-scale TX11 Motor No. 5

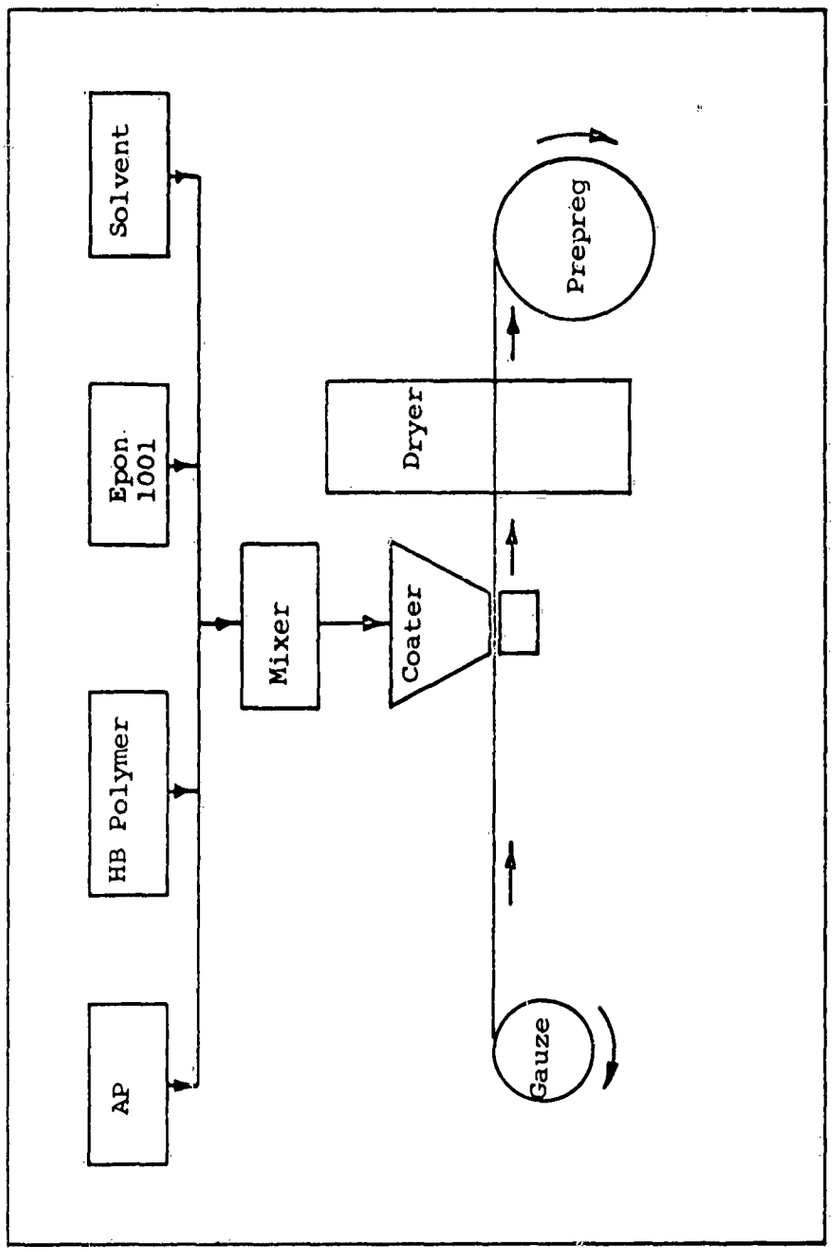


Figure 70. Anticipated Prepregging Process for Combustible Core Manufacture

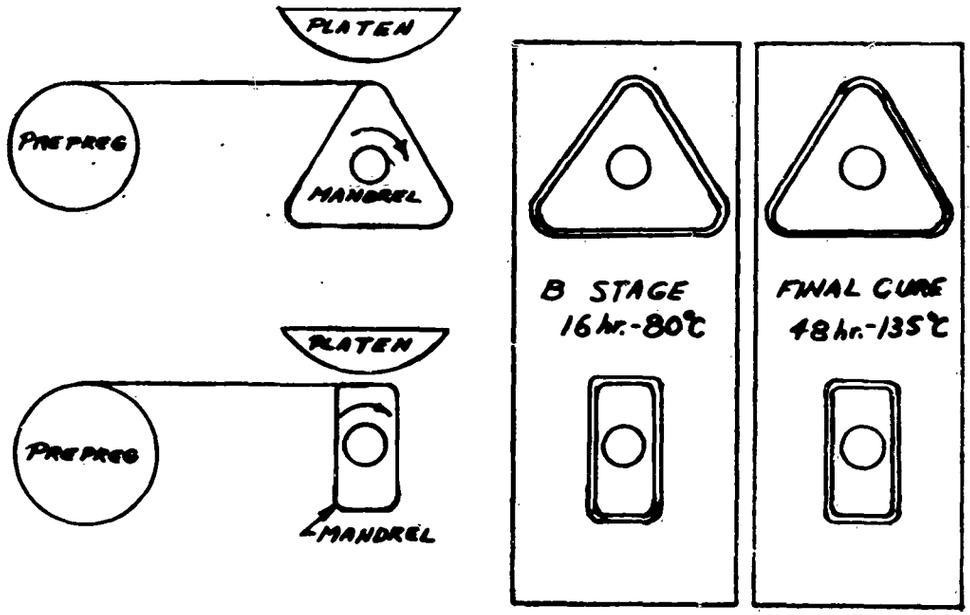


Figure 71. Anticipated Winding and Cure Processes for Combustible Core Manufacture

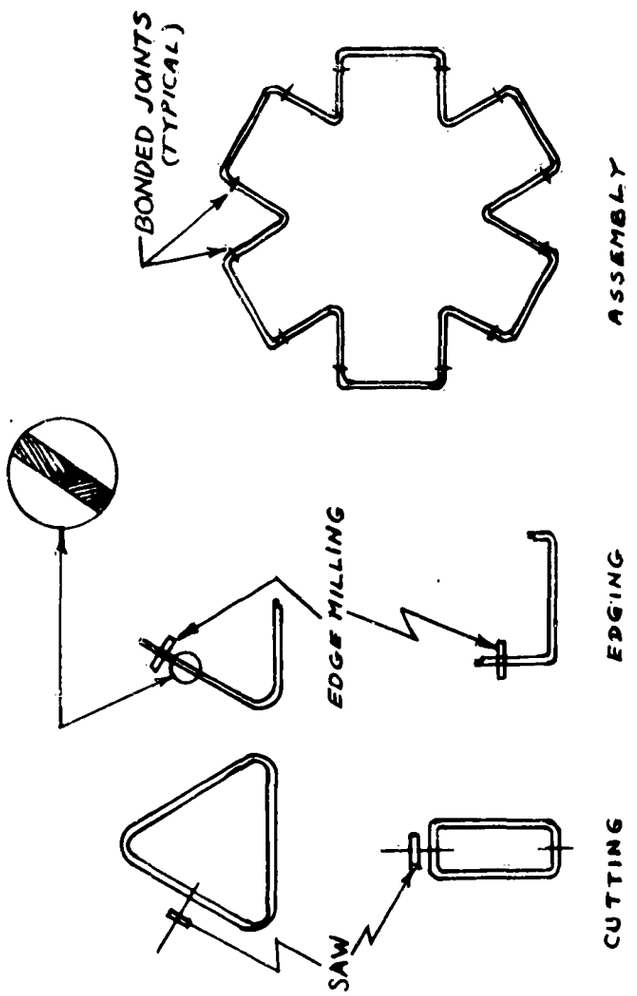


Figure 72. Anticipated Cutting and Fabricating Processes for Combustible Core Manufacture

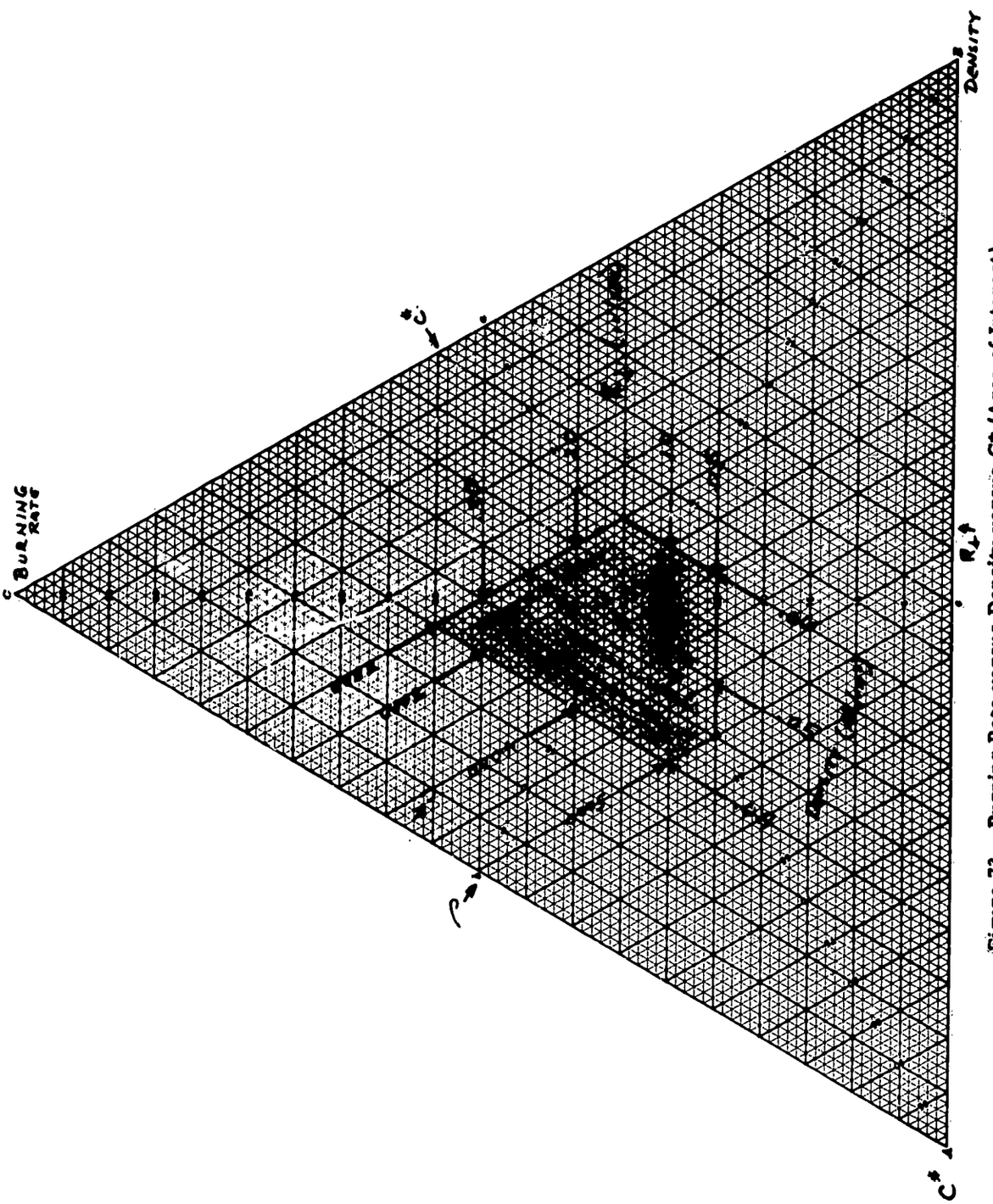


Figure 73. Burning Rate versus Density versus C* (Area of Interest).

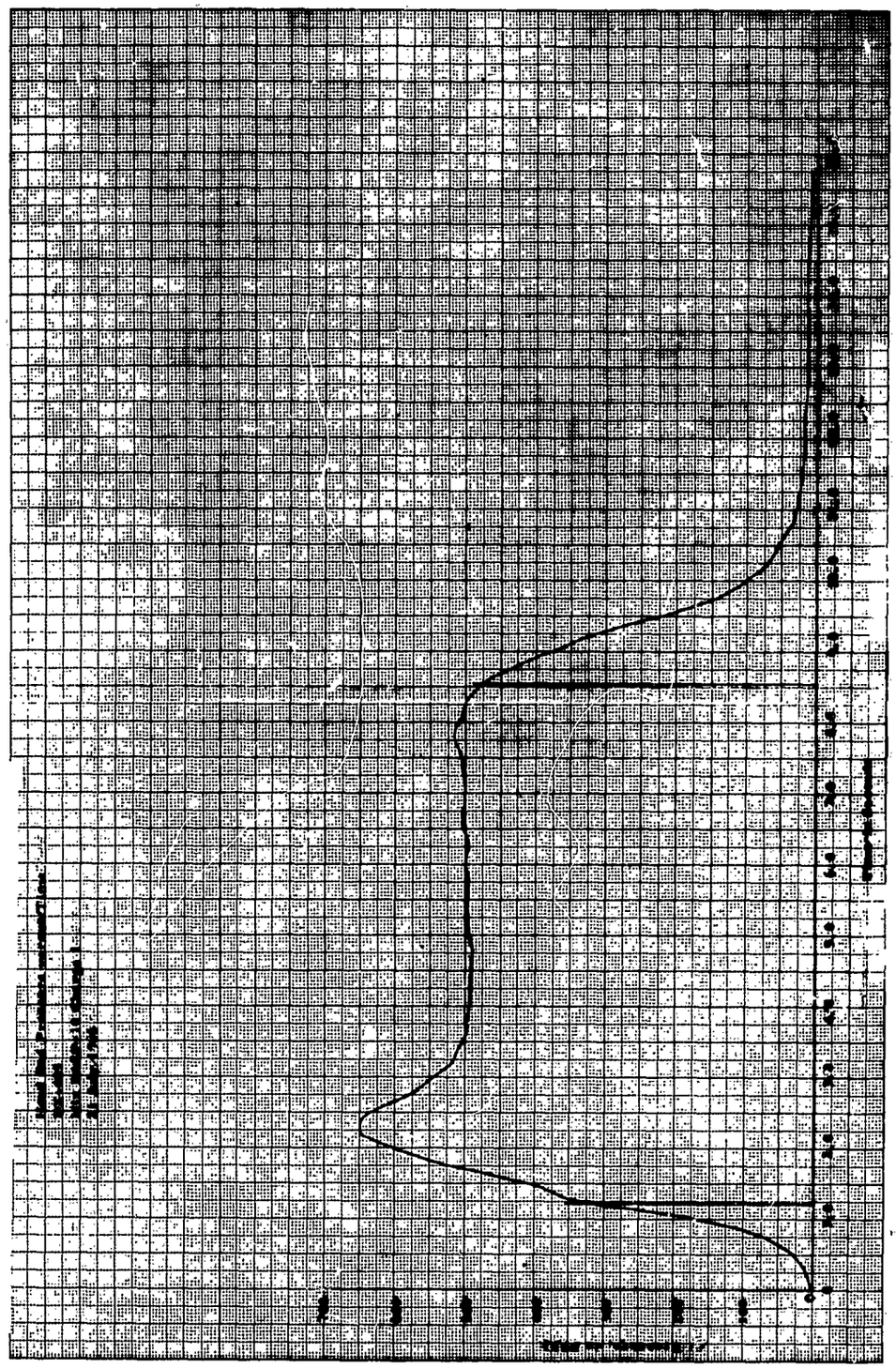


Figure 74. Pressure Versus Time Trace, TX405 Motor No. 1

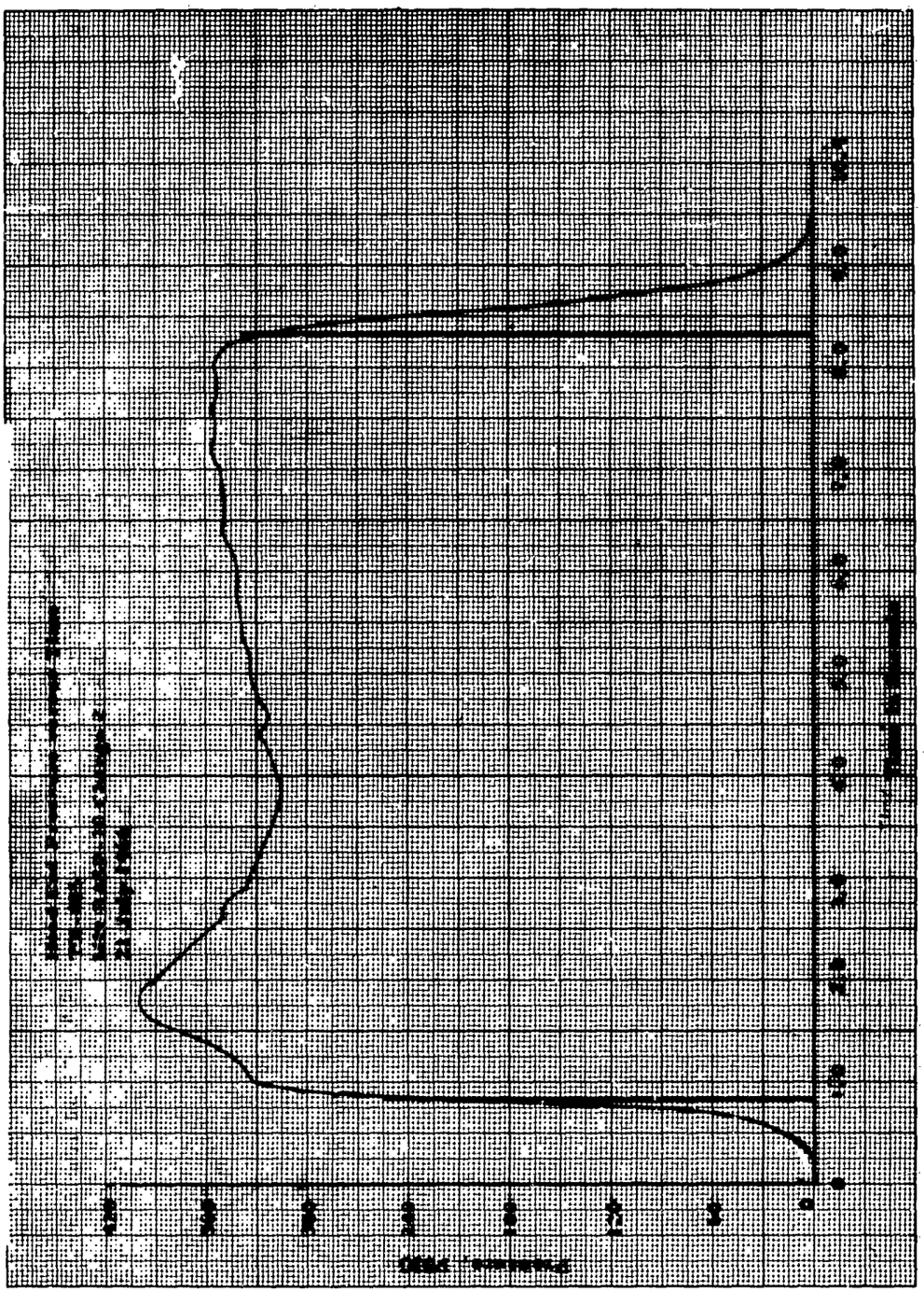


Figure 75. Pressure versus Time Trace, TX405 Motor No. 2.

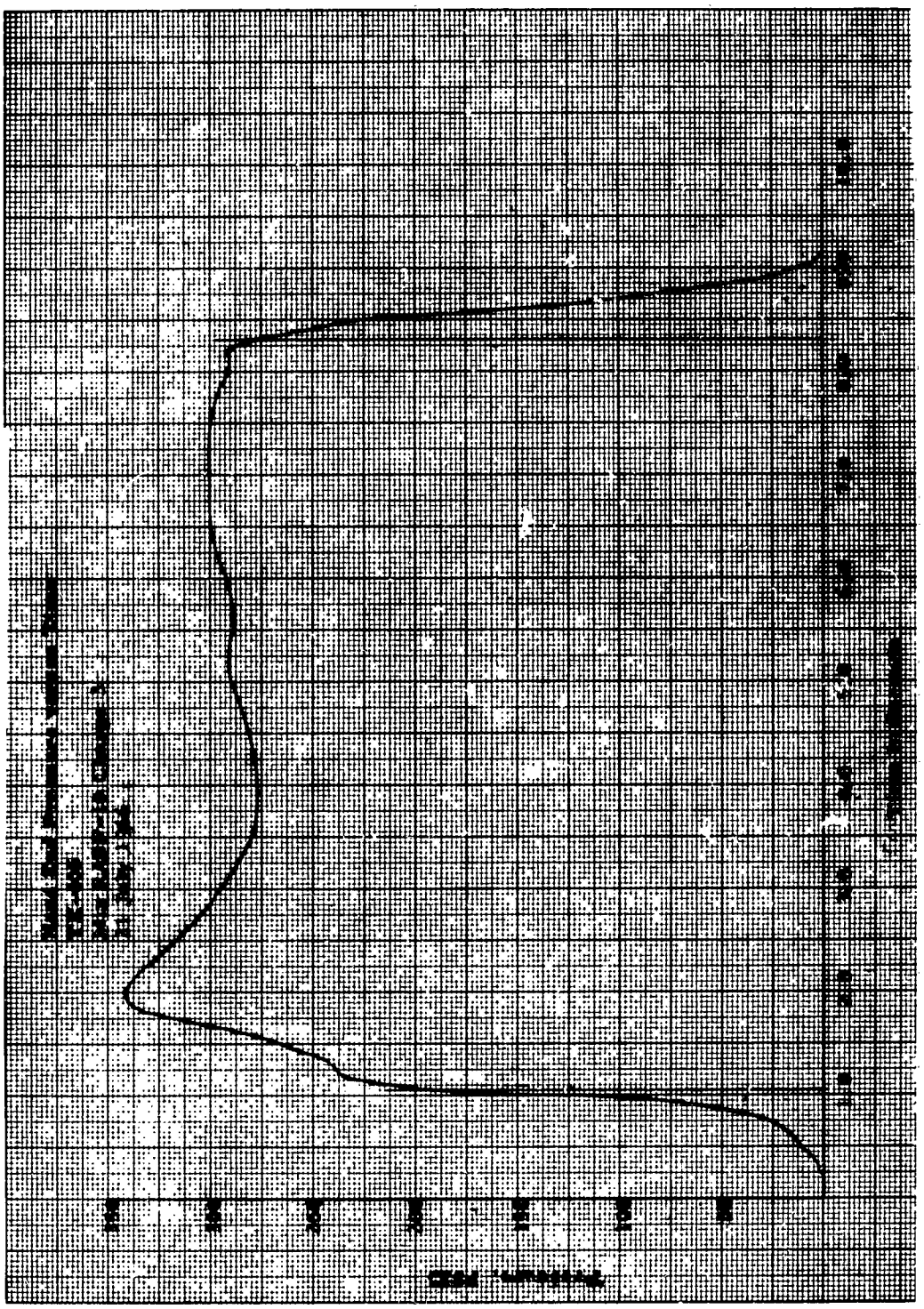


Figure 76. Pressure Versus Time Trace, TX405 Motor No. 3

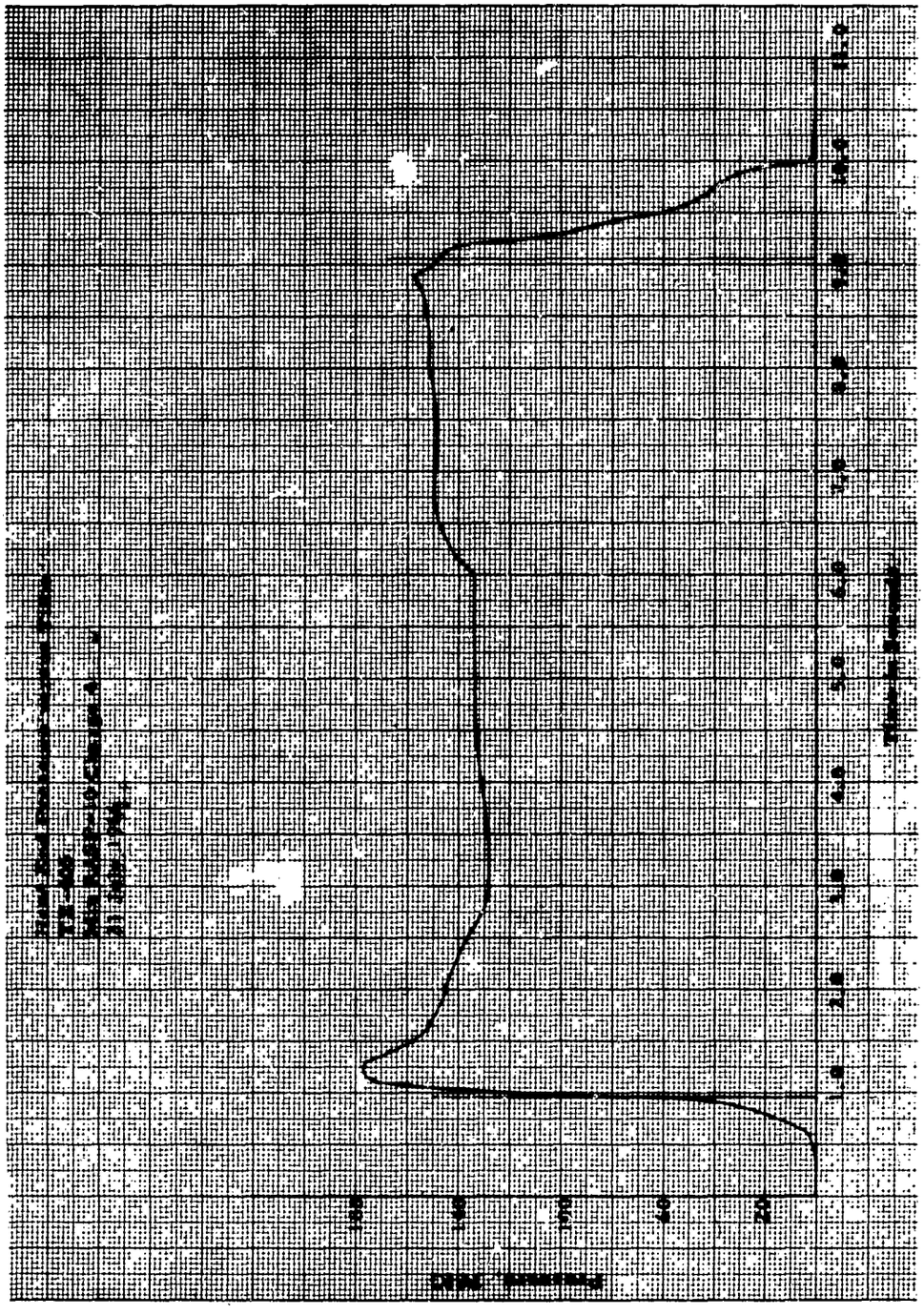


Figure 77. Pressure Versus Time Trace, TX405 Motor No. 4

Figure 78. Pressure Versus Time Trace, TX405 Motor No. 1, Mix 14

Figure 79. Pressure Versus Time Trace, TX405 Motor No. 1, Mix 15

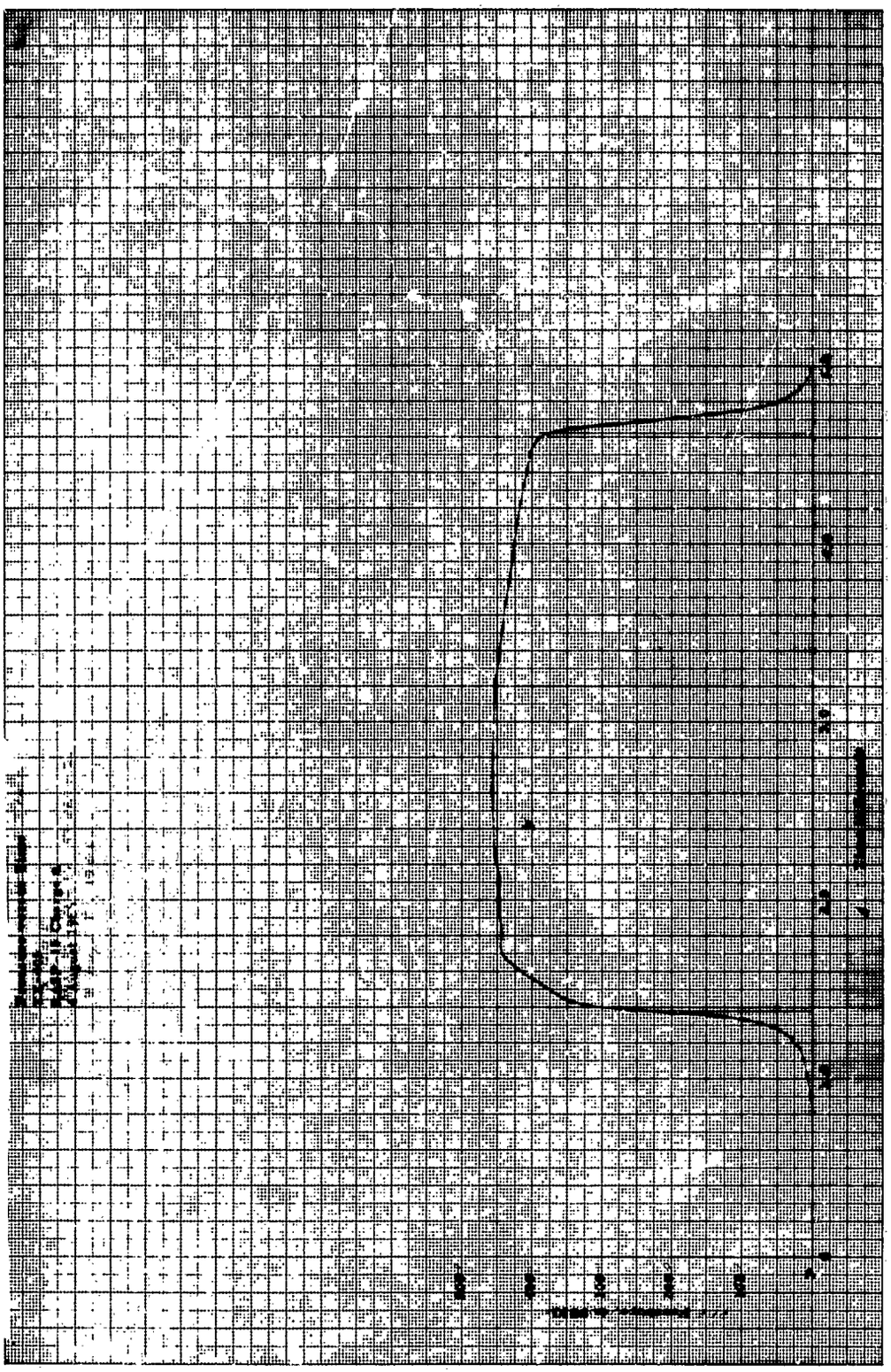


Figure 80. Pressure Versus Time Trace, TX405 Motor No. 2, Mix 15

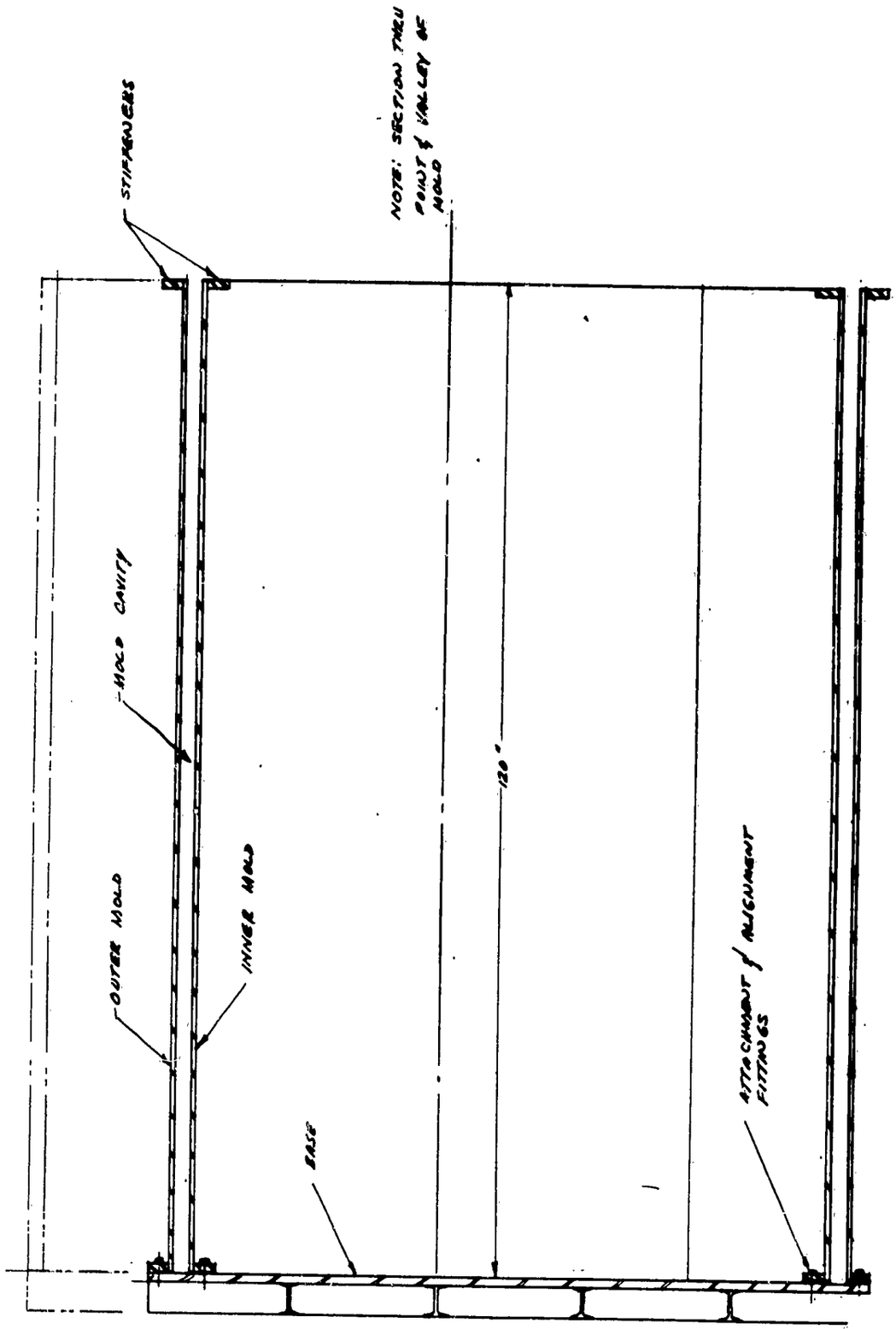


Figure 81. Longitudinal Cross Section of Core Mold

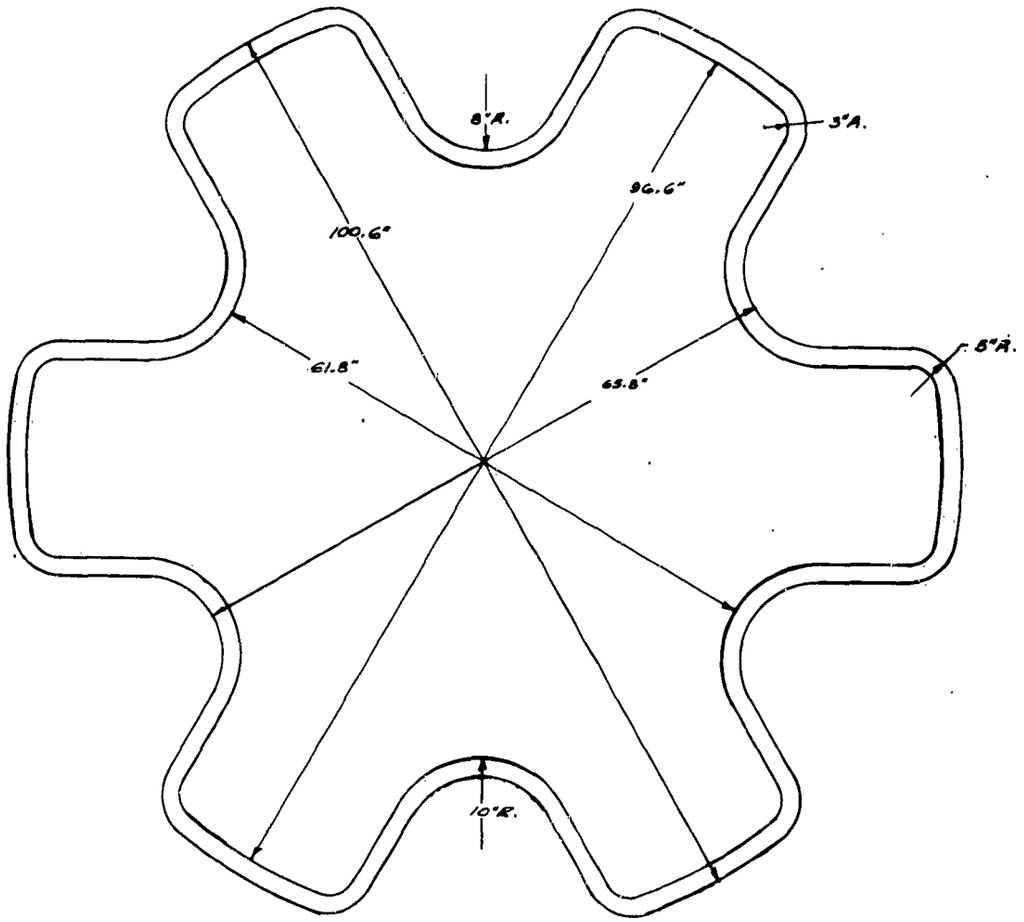


Figure 82. Cross Section of Cast Core Configuration

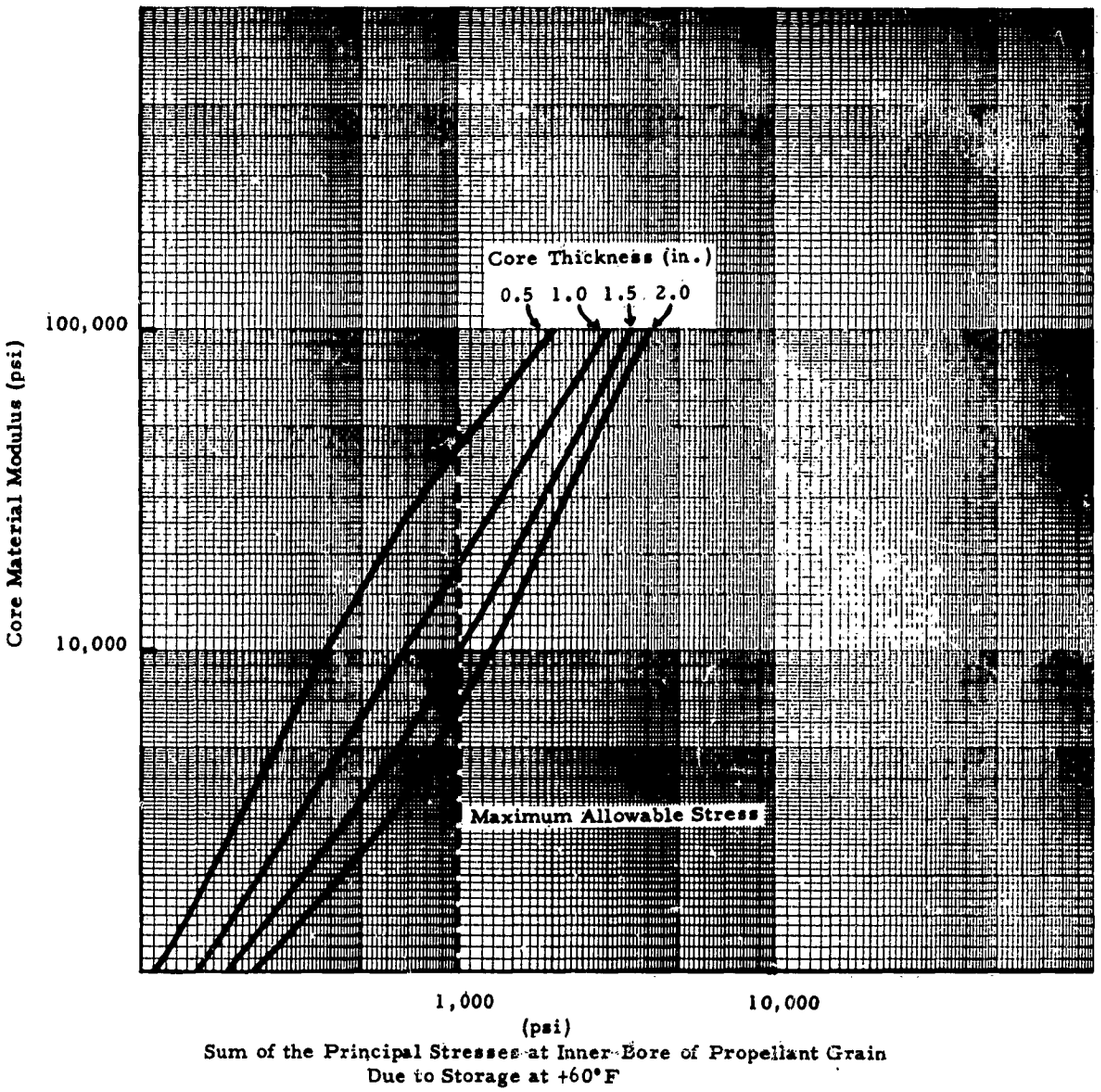


Figure 83. Core Material Modulus versus Core-Propellant Interface Stresses

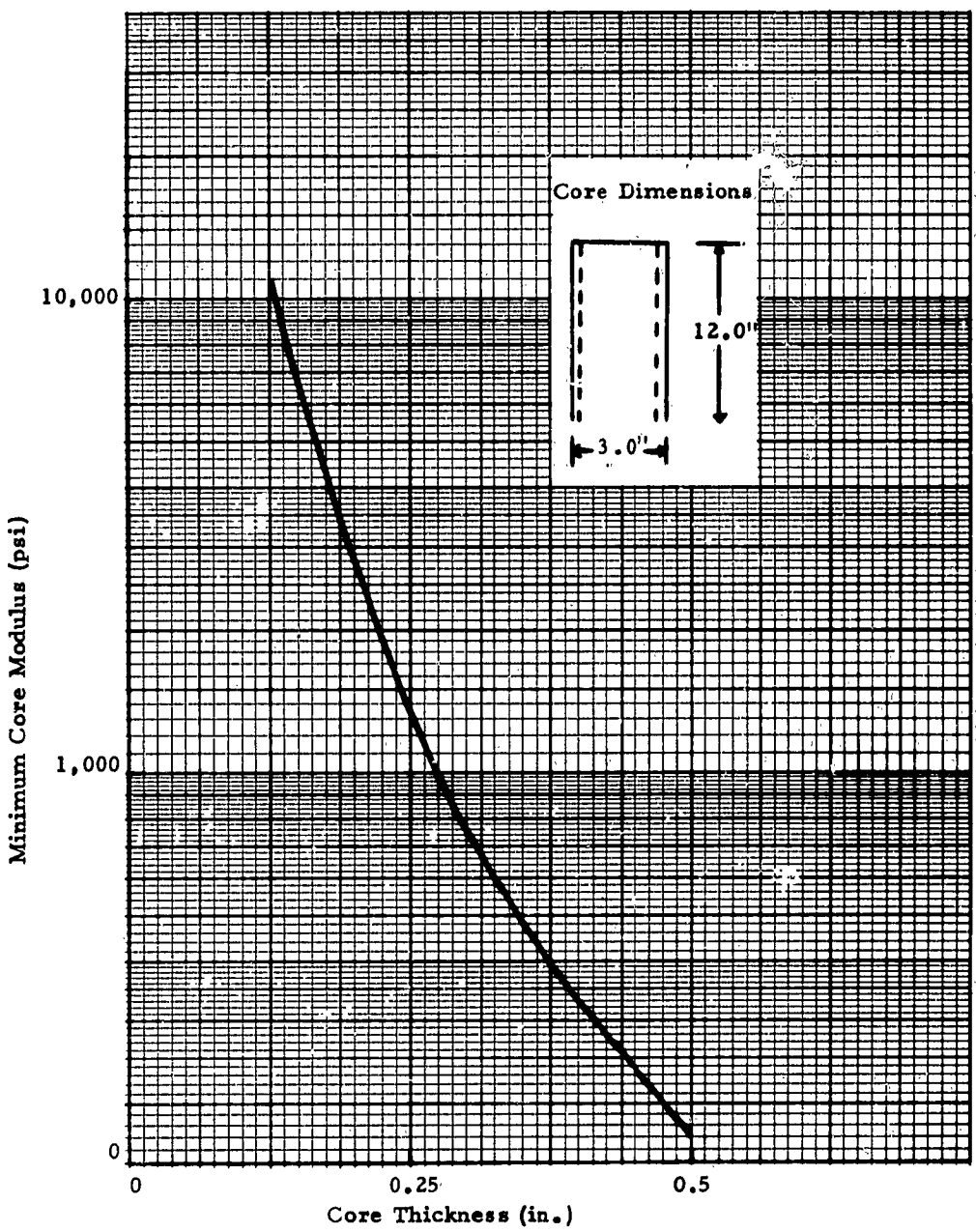


Figure 84. Core Modulus Required to Resist Buckling Due to Hydrostatic Head of Propellant (Safety Factor - 2.0)

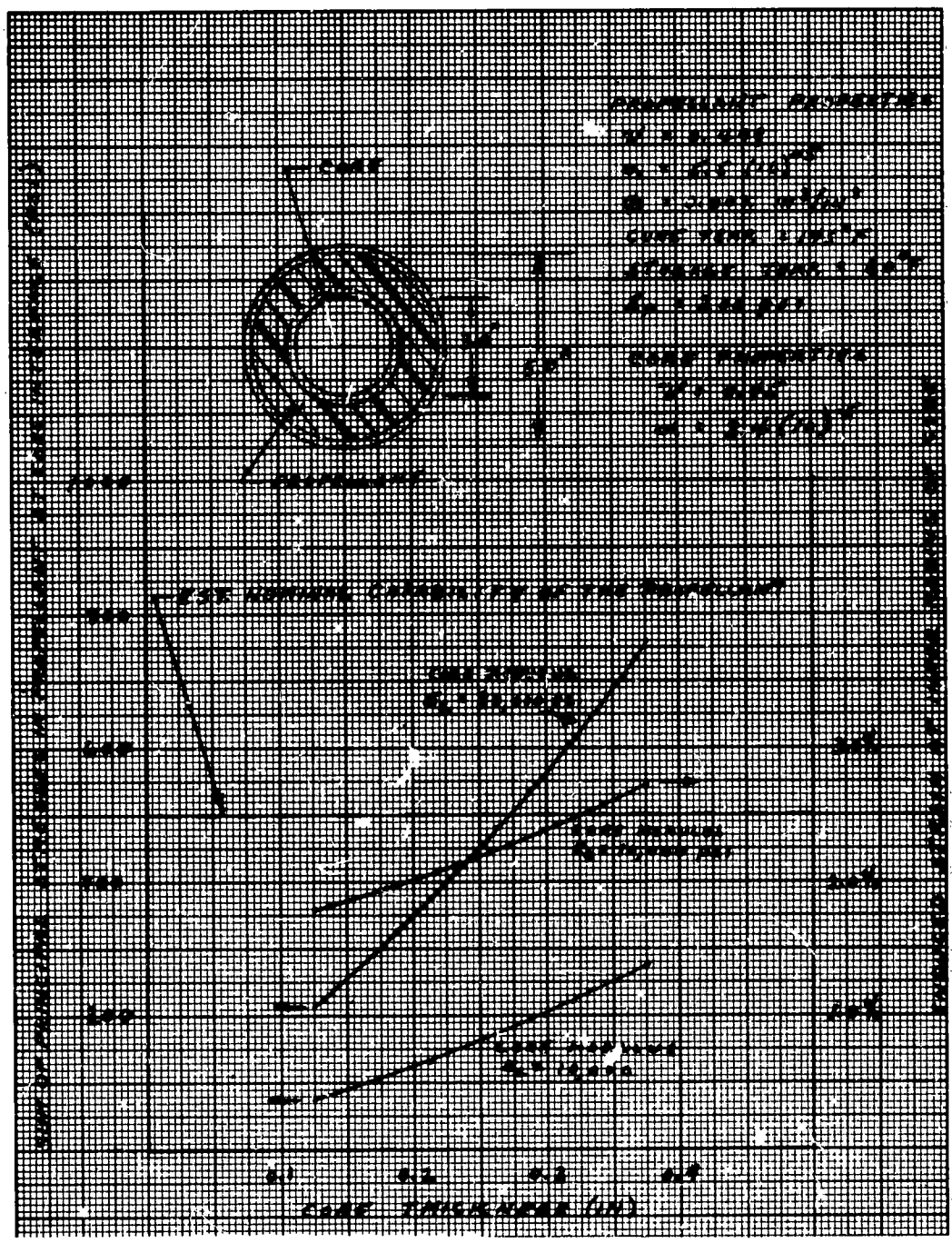


Figure 85. Core Thickness as a Function of Principal Stresses, Induced Strain and Modulus

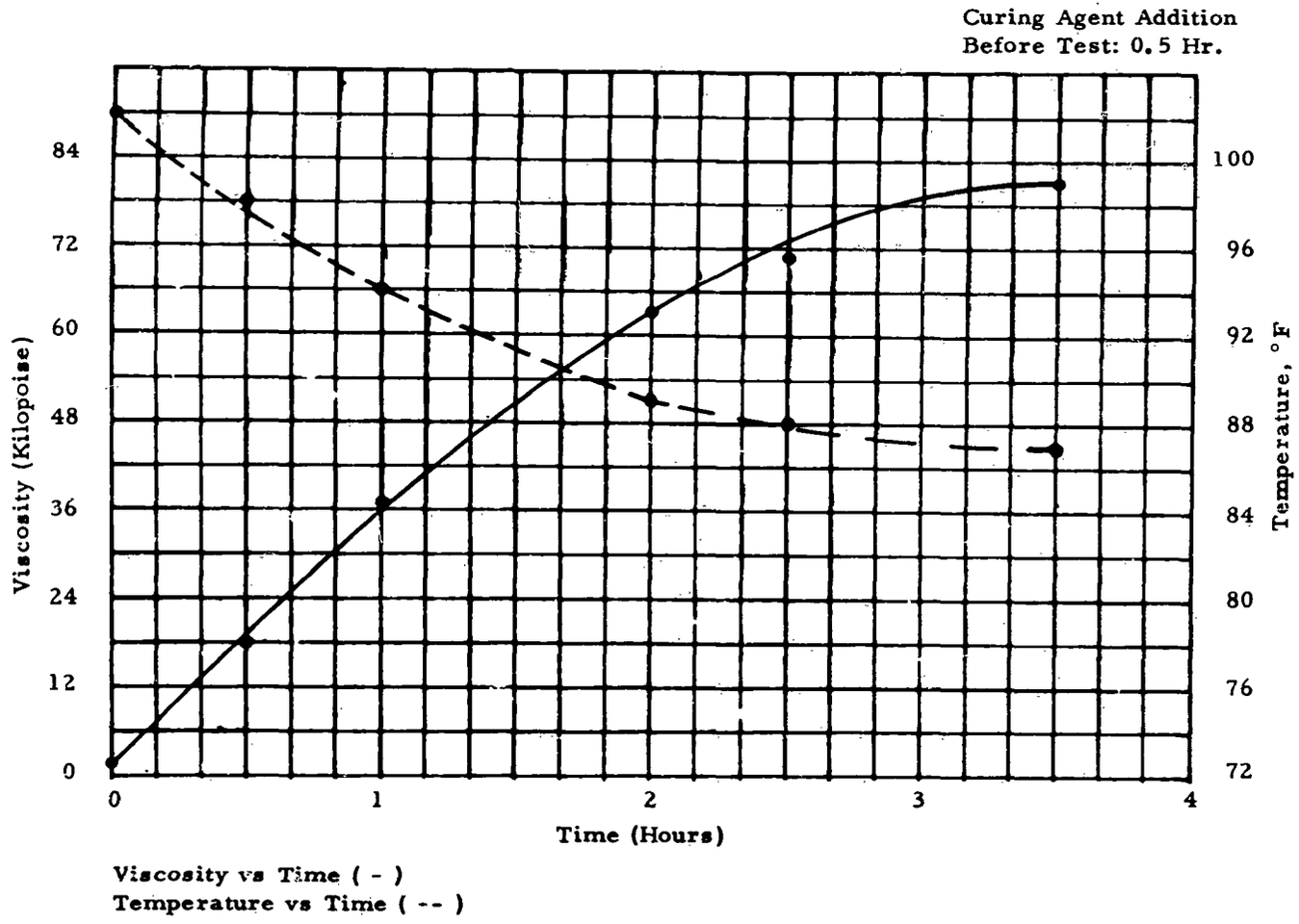
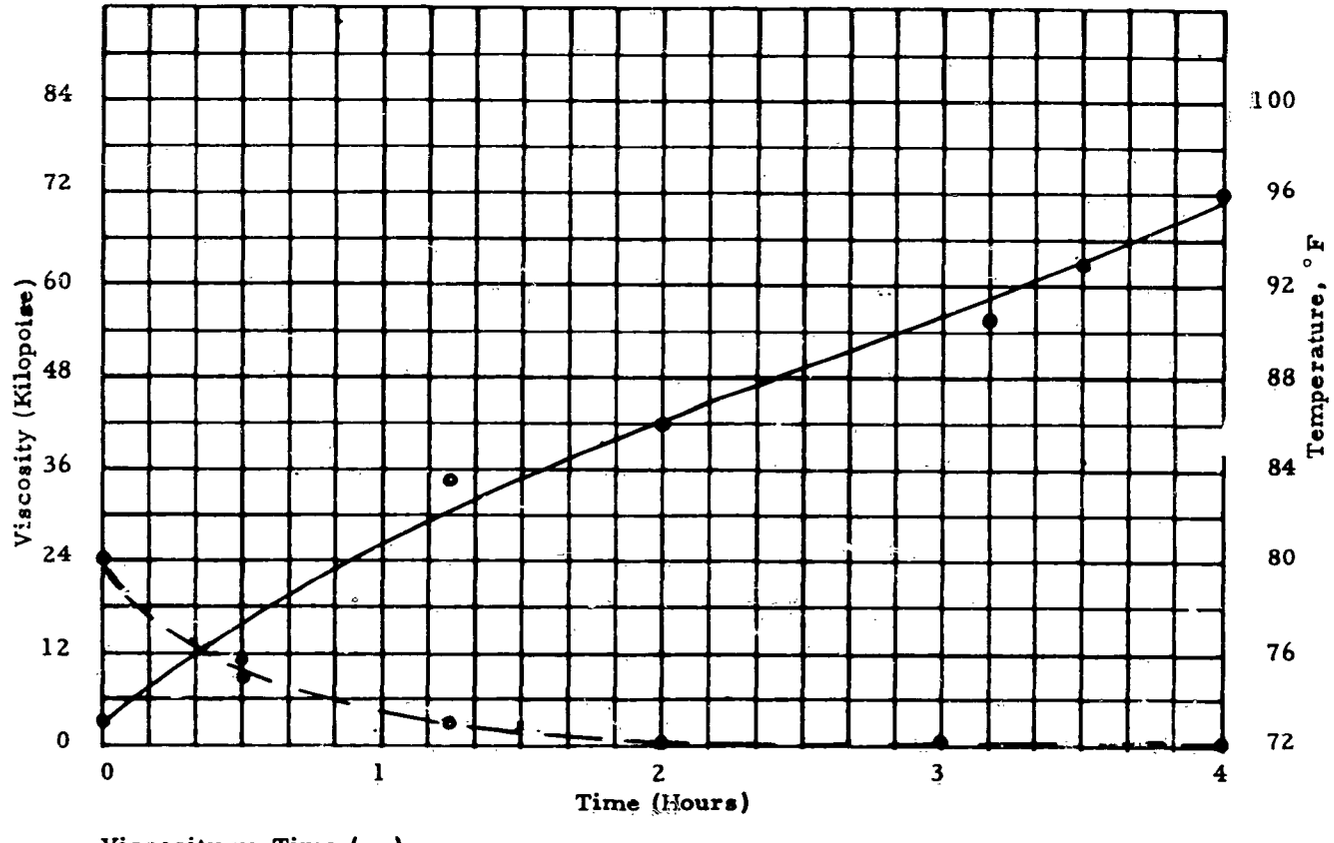


Figure 86. Processibility of Mix 12Q915.

UNCLASSIFIED

Curing Agent Addition
Before Test: 0.5 Hr.



Viscosity vs Time (-)

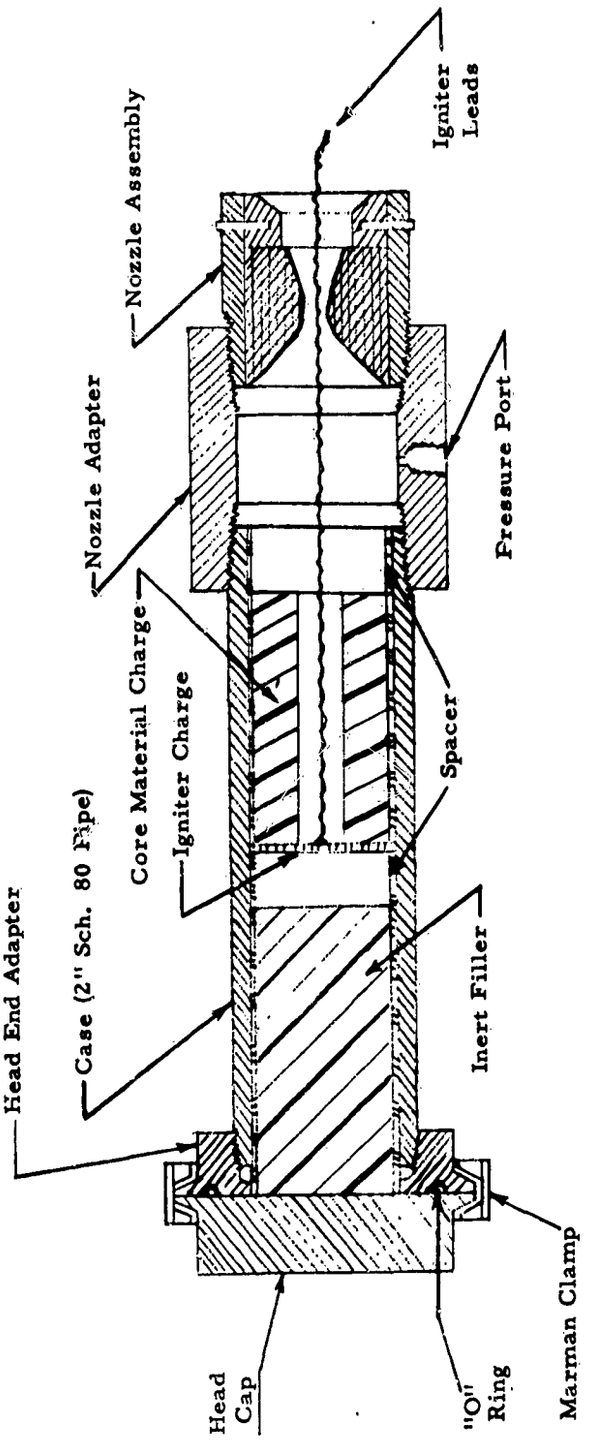


Figure 88. Typical TX-405 (T-Burner) Motor with Single Propellant Charge

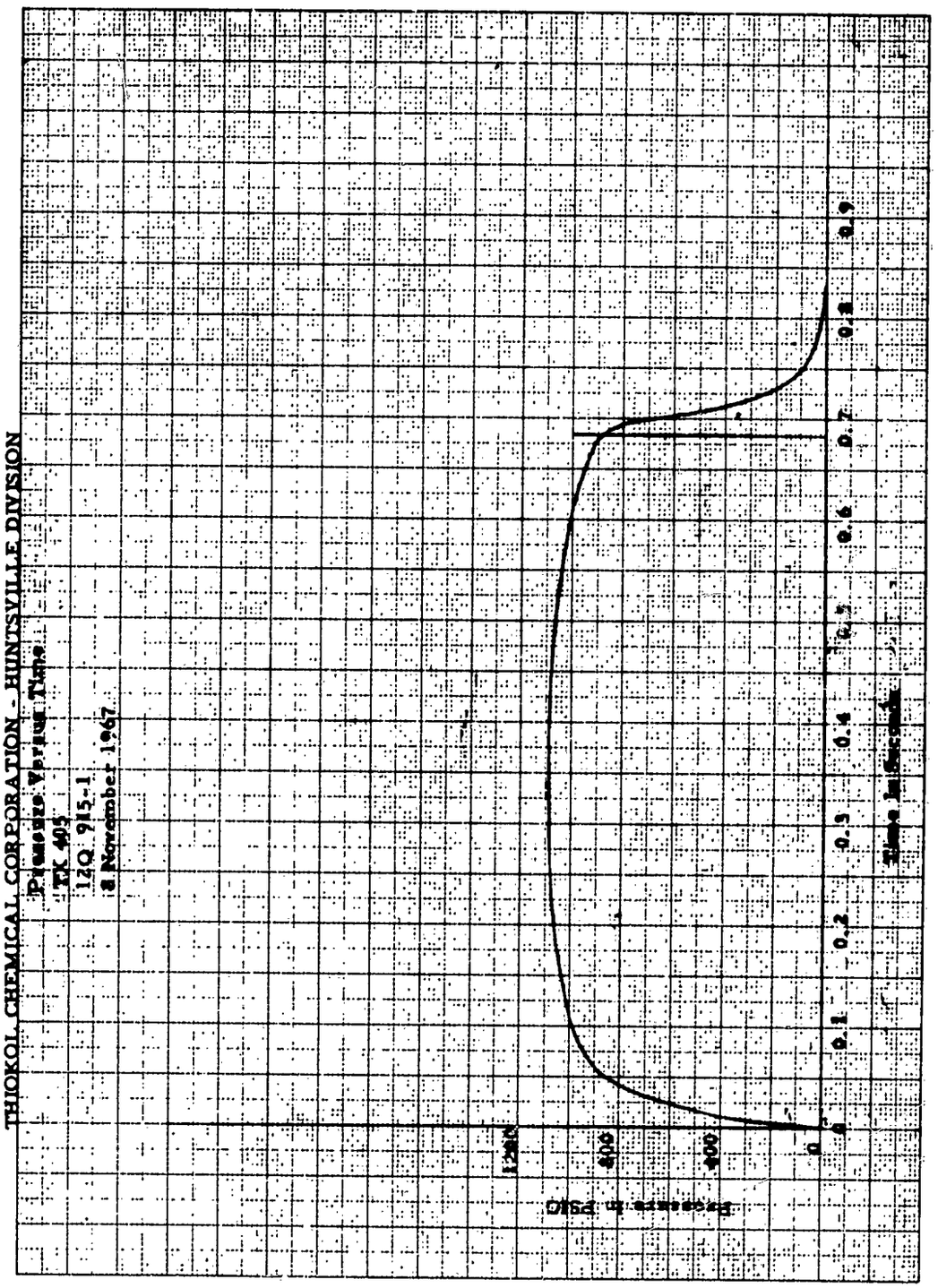


Figure 89. Pressure Versus Time Trace, Mix 12Q915, Charge 1 (TX405)

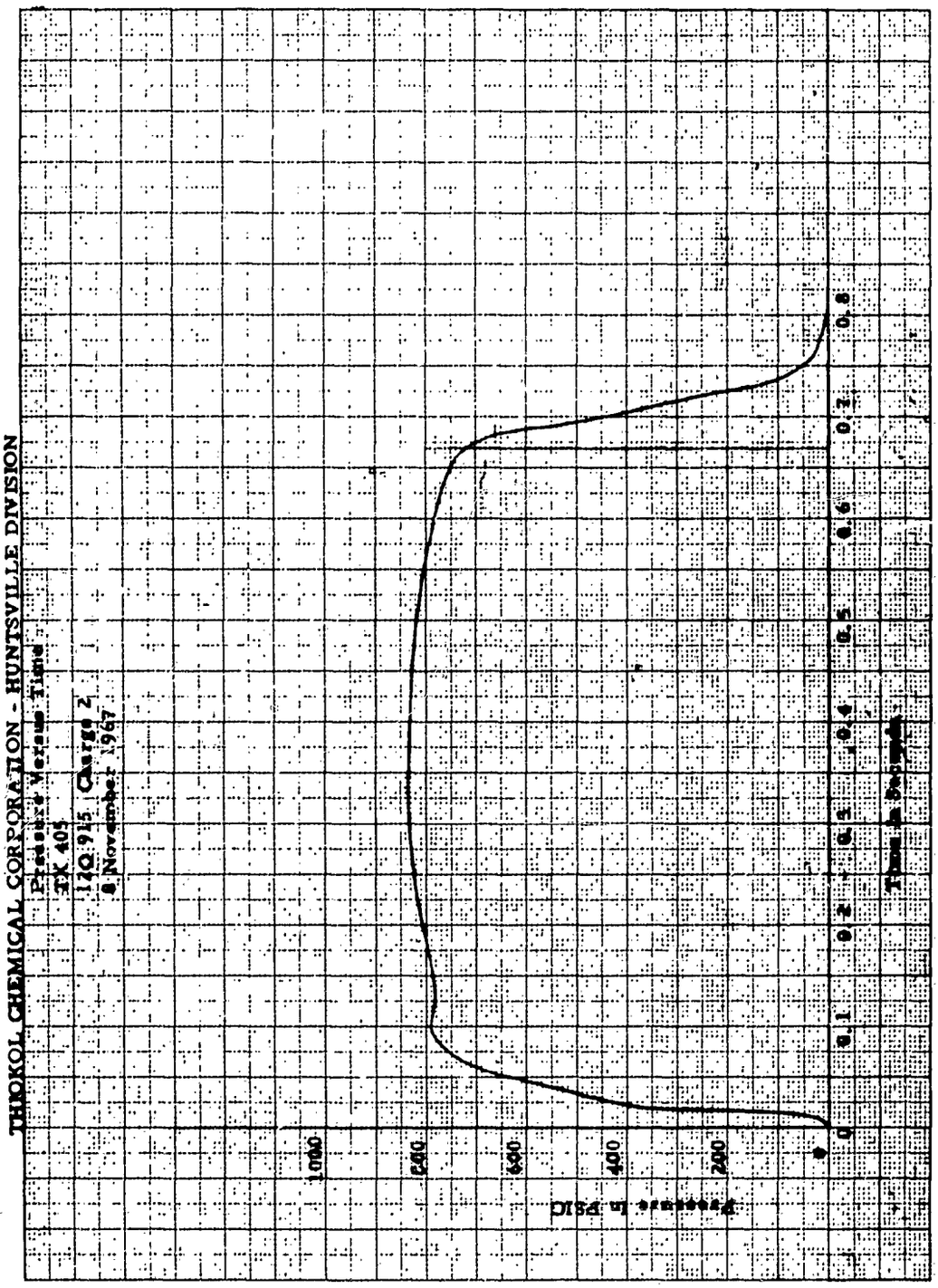


Figure 90. Pressure Versus Time Trace, Mix 11Q915, Charge 2 (TX405)

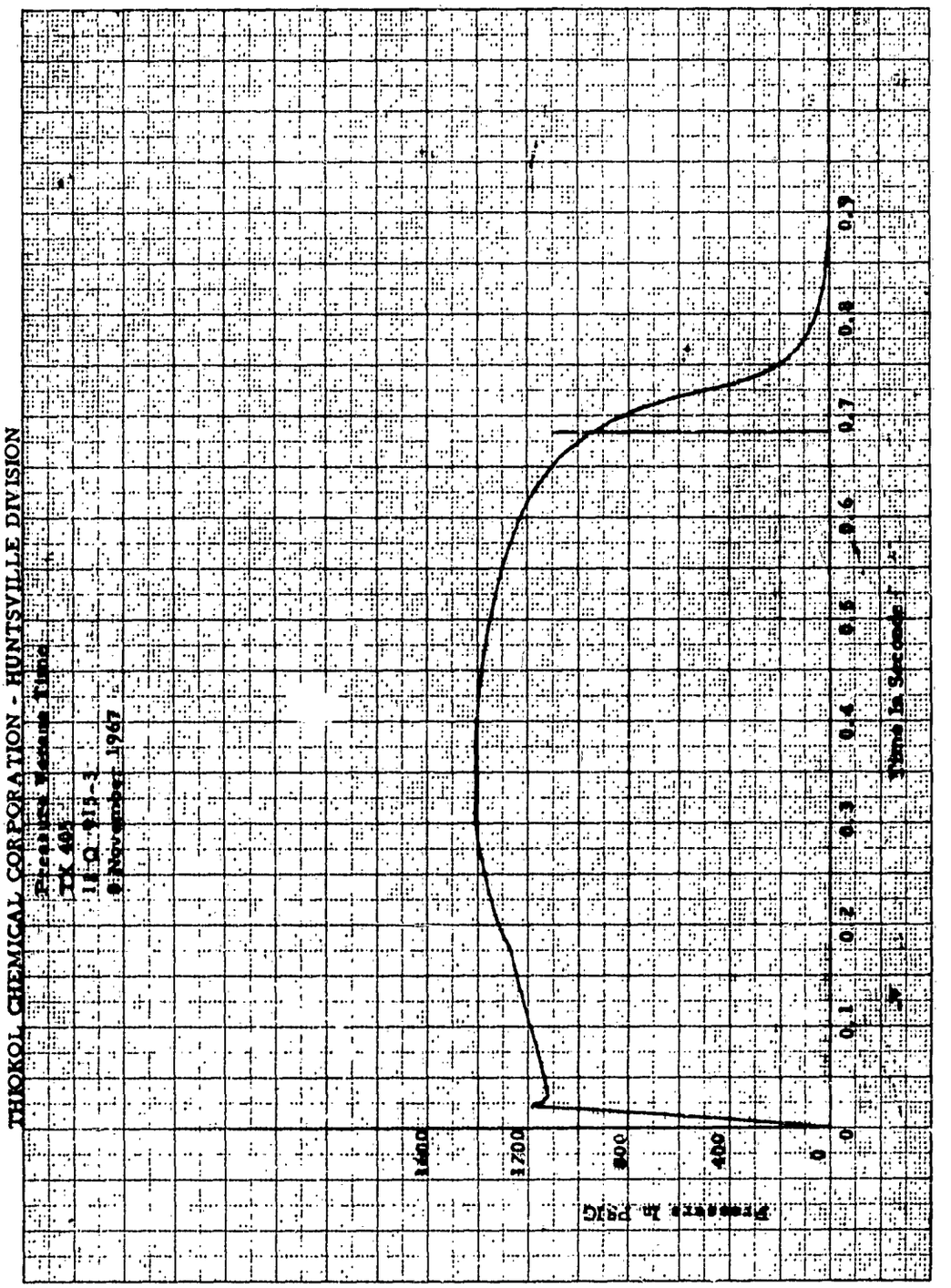


Figure 91. Pressure Versus Time Trace, Mix 12Q915, Charge 3 (TX405)

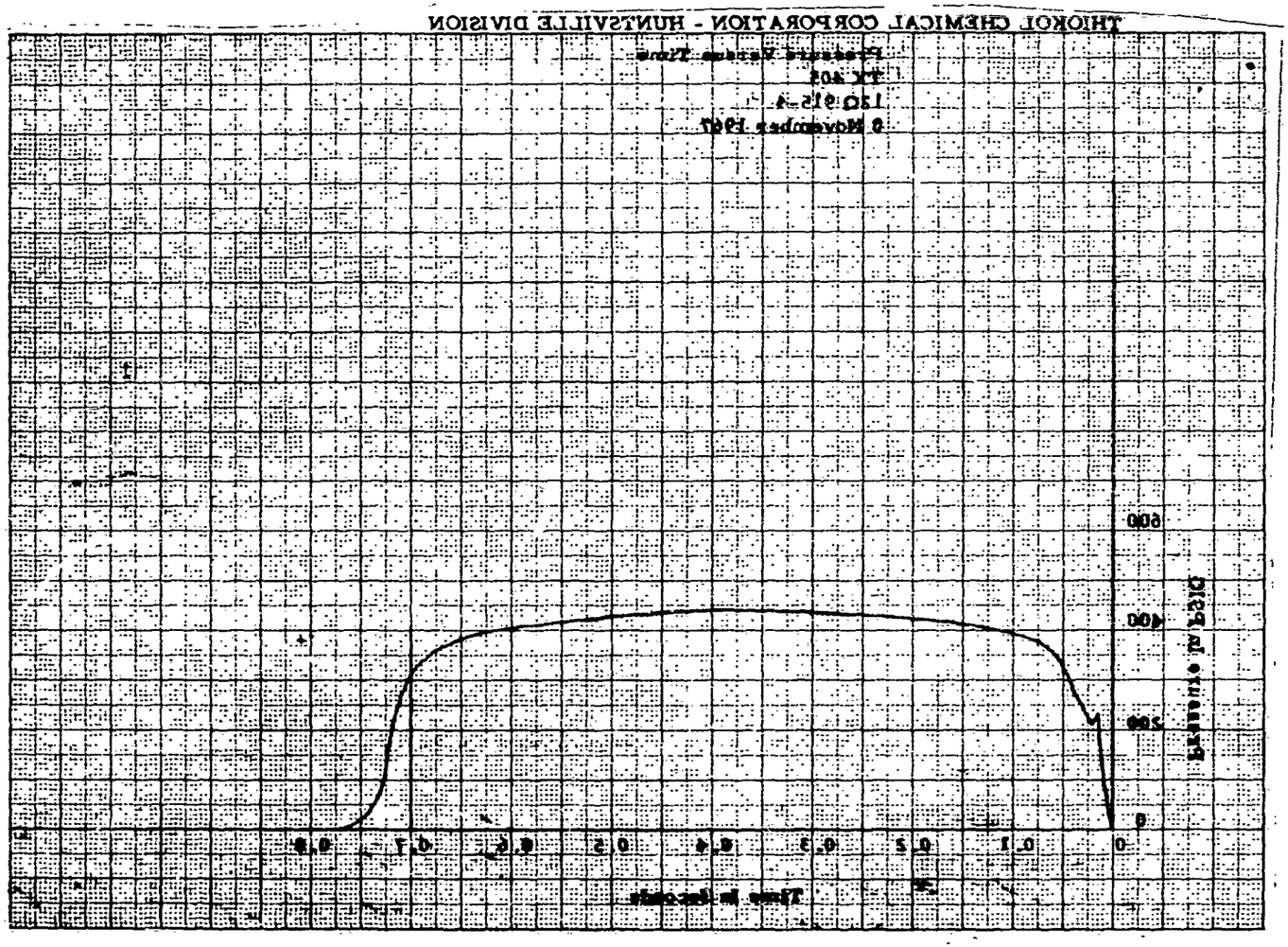


Figure 92. Pressure Versus Time Trace, Mix 12Q915, Charge 4 (TX405)

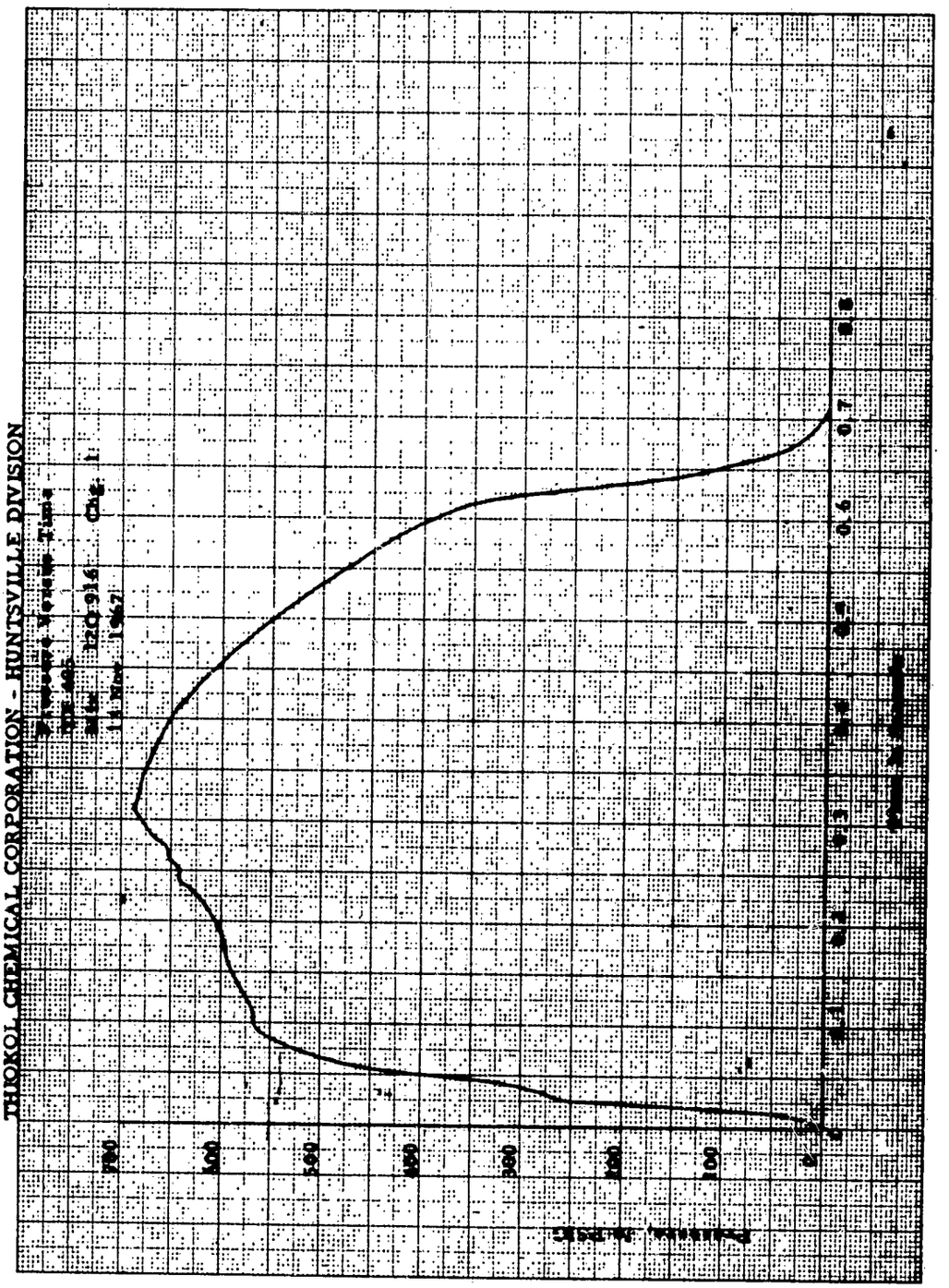


Figure 93. Pressure Versus Time Trace, Mix 12Q916, Charge 1 (TX405)

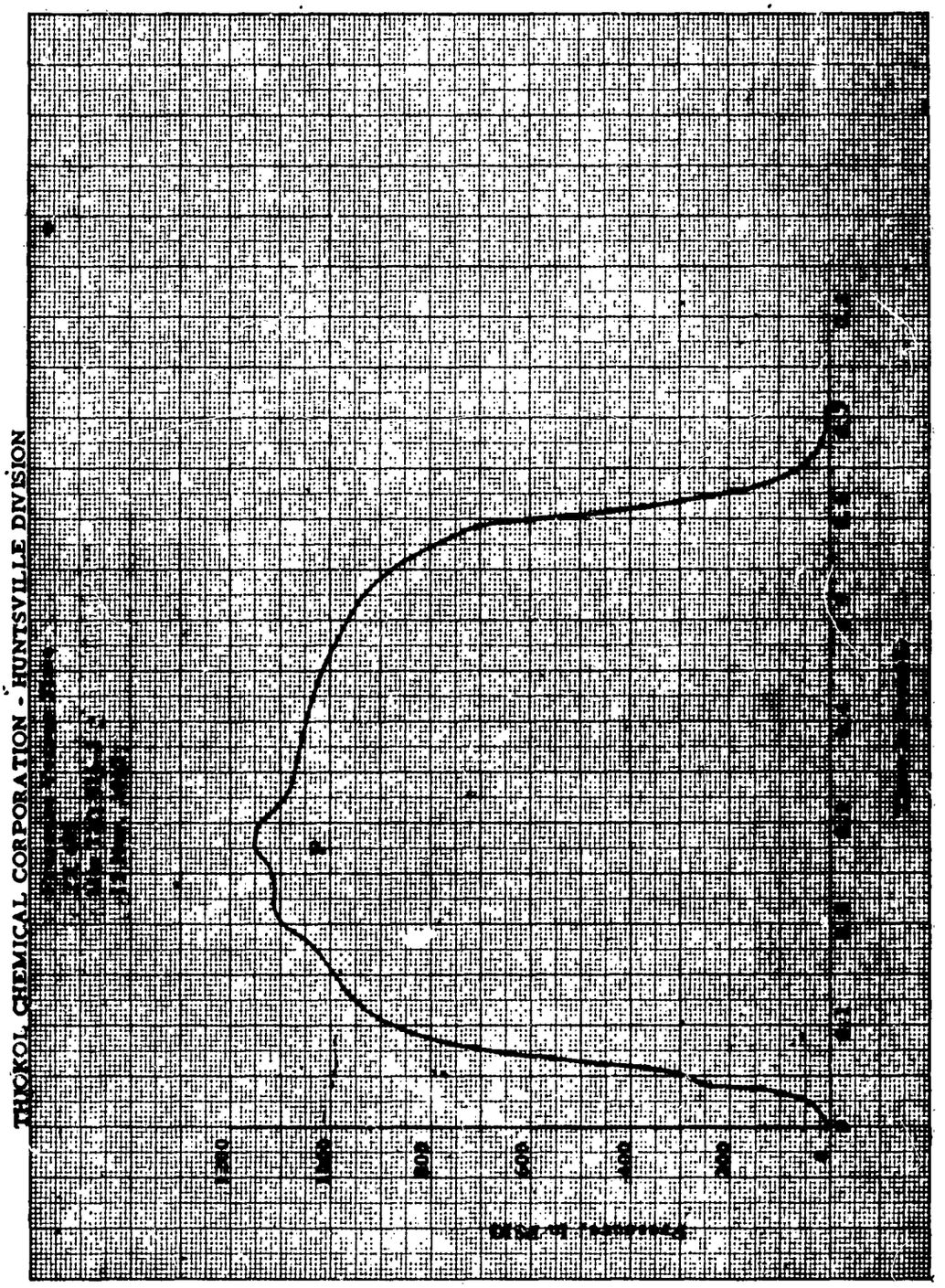


Figure 94. Pressure Versus Time Trace, Mix 12Q916, Charge 2 (TX405)

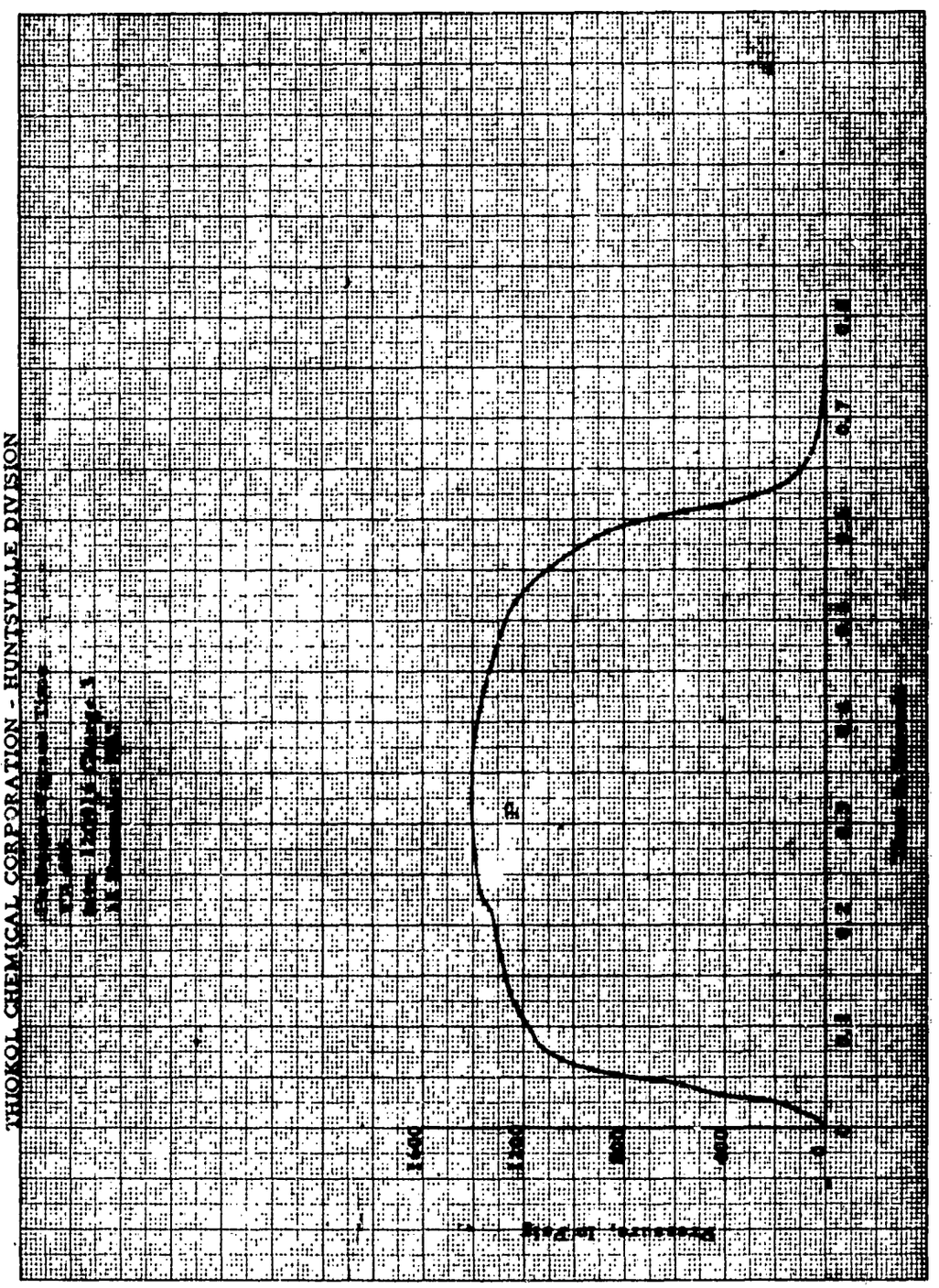


Figure 95. Pressure Versus Time Trace, Mix 12Q916, Charge 3 (TX405)

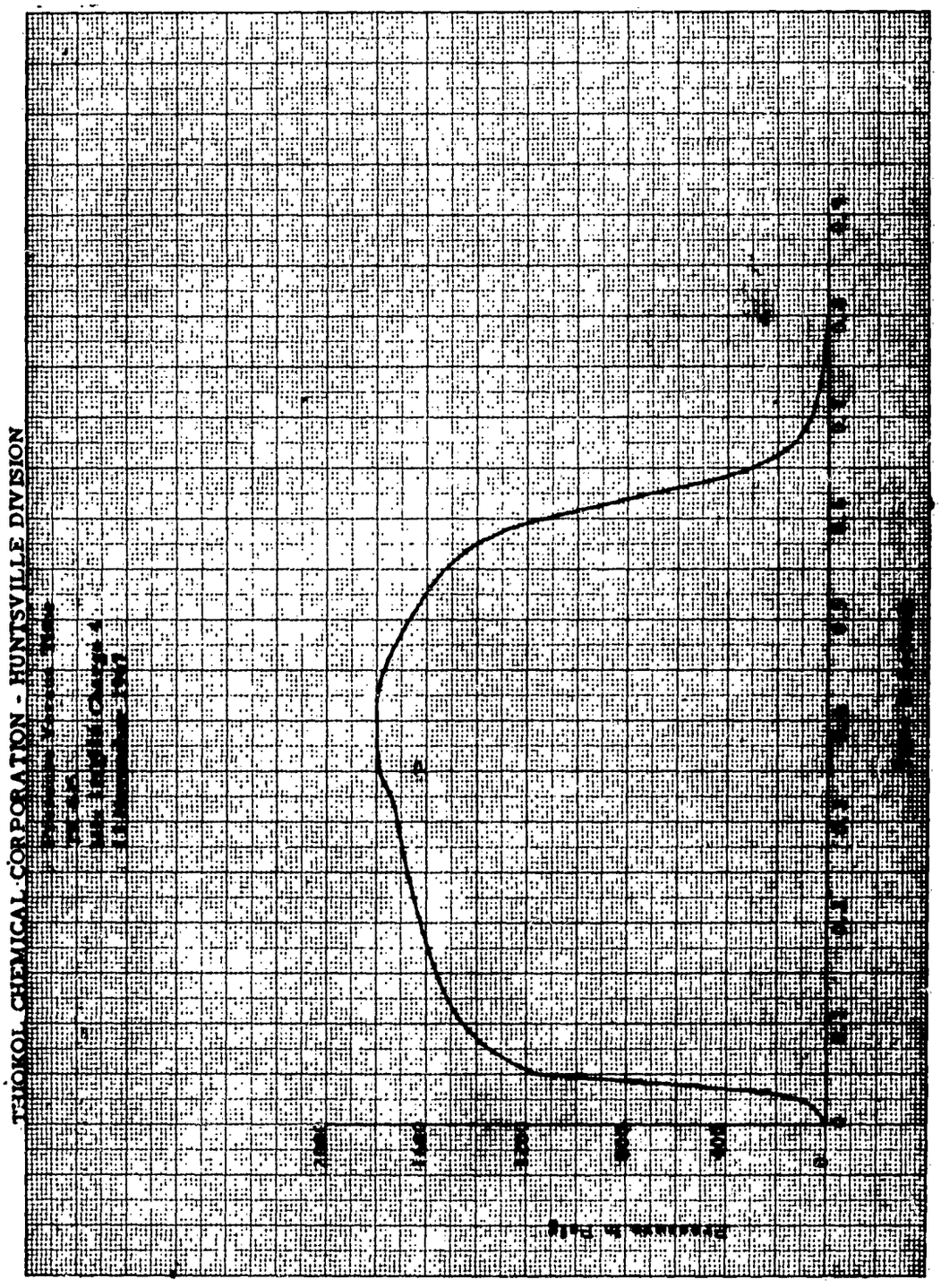


Figure 96. Pressure Versus Time Trace, Mix 12Q916, Charge 4 (TX405)

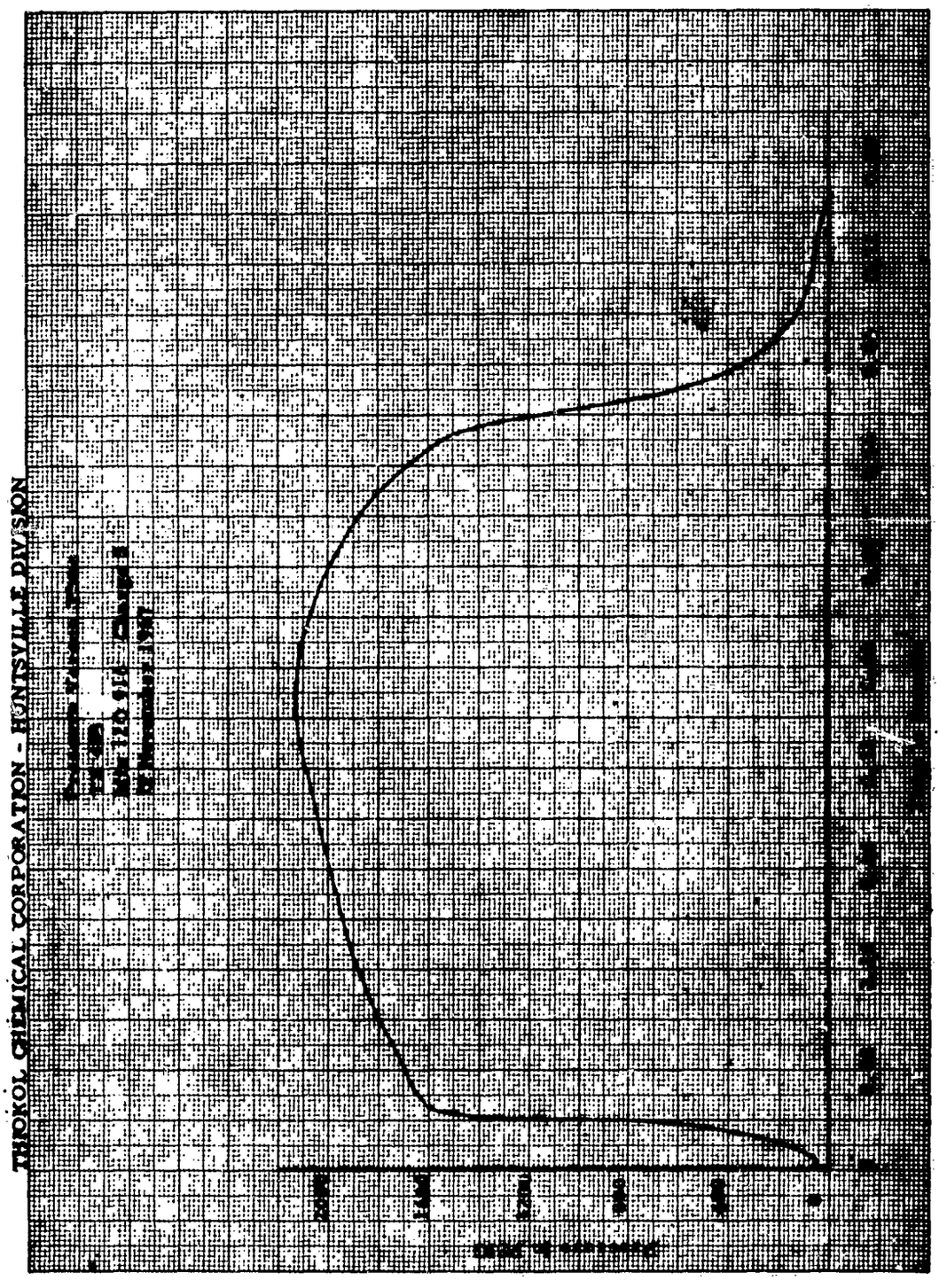


Figure 97. Pressure Versus Time Trace, Mix 12Q916, Charge 5 (TX405)

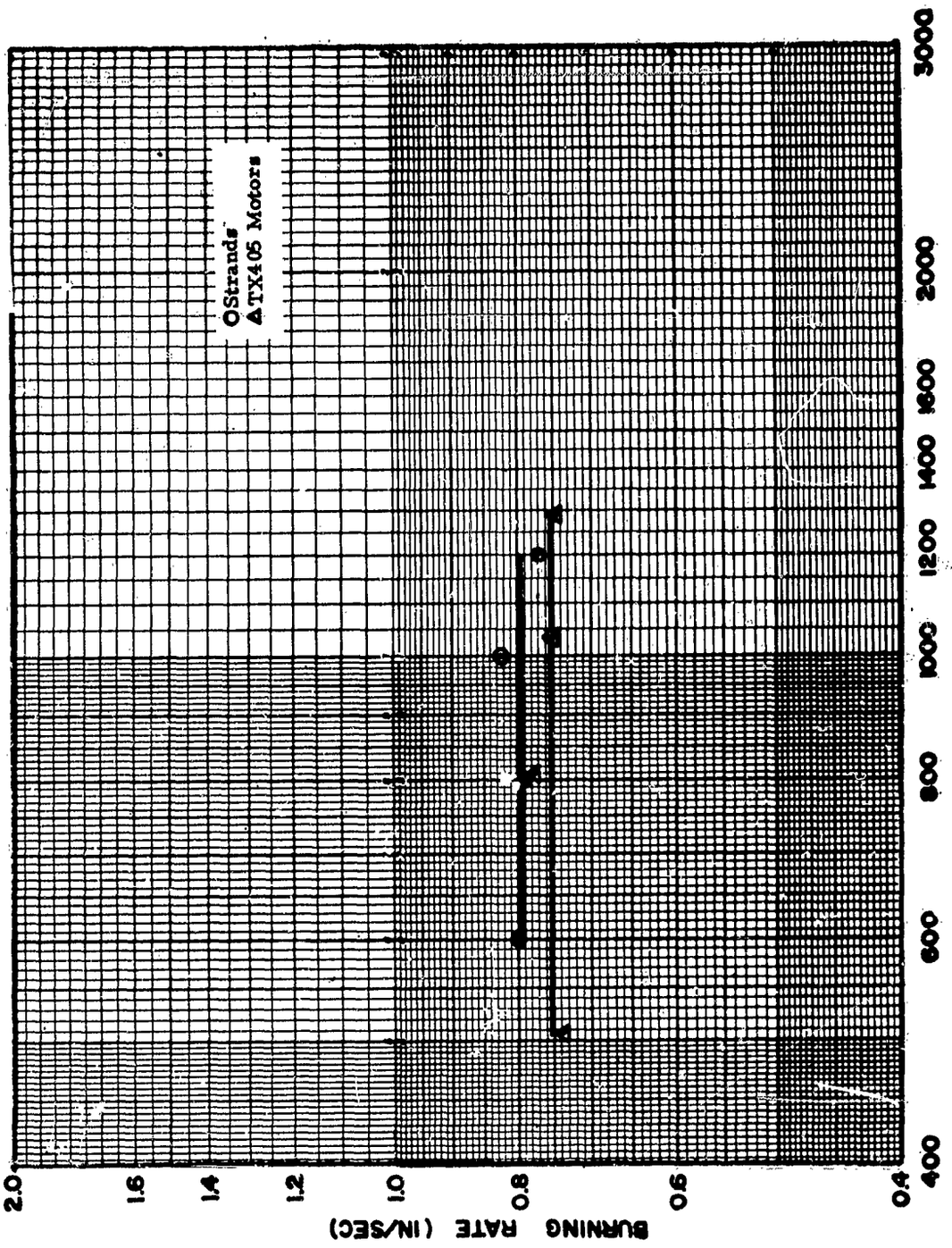


Figure 98. Burning Rate Versus Pressure, Mix 120915.

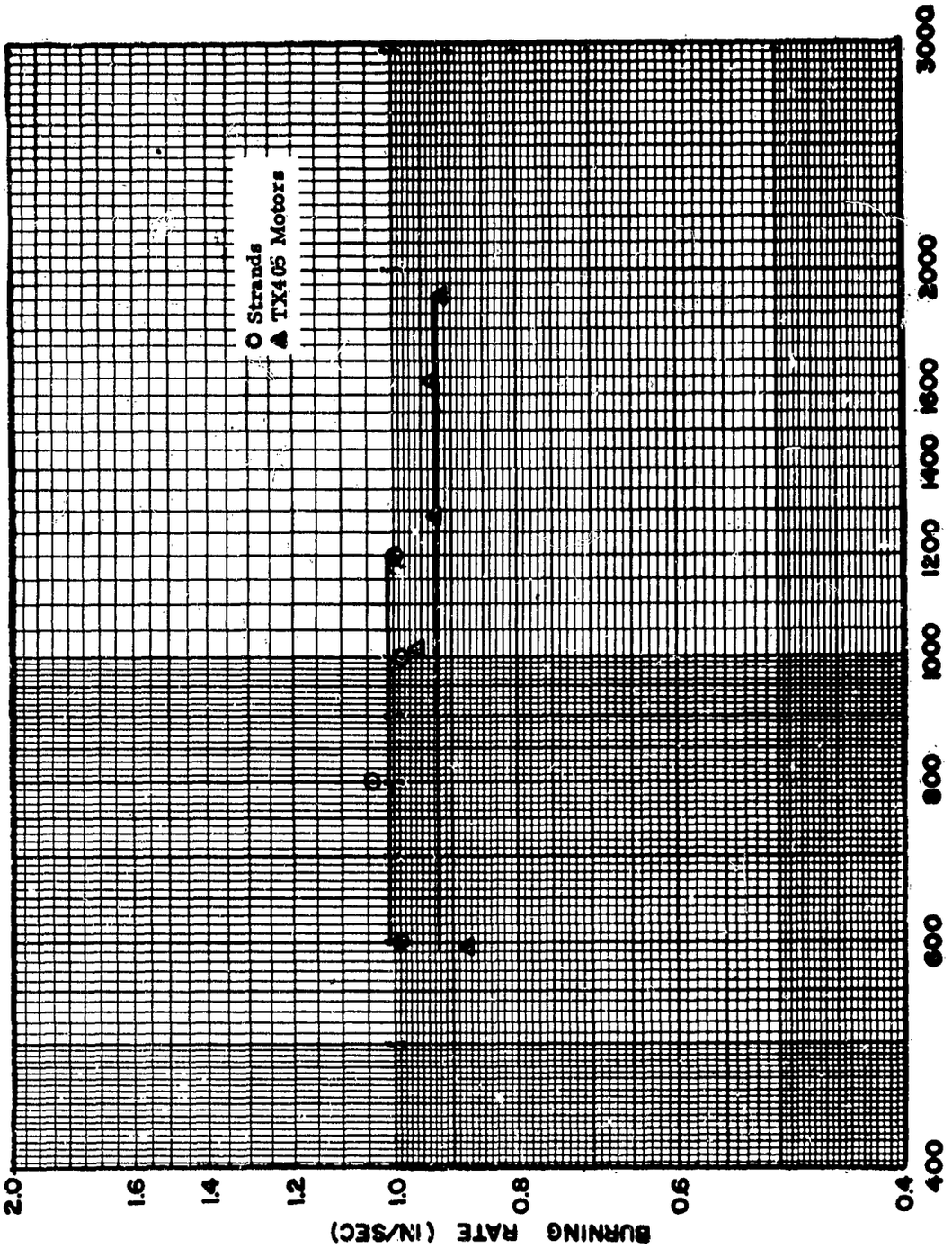


Figure 99. Burning Rate Versus Pressure, Mix 120916.

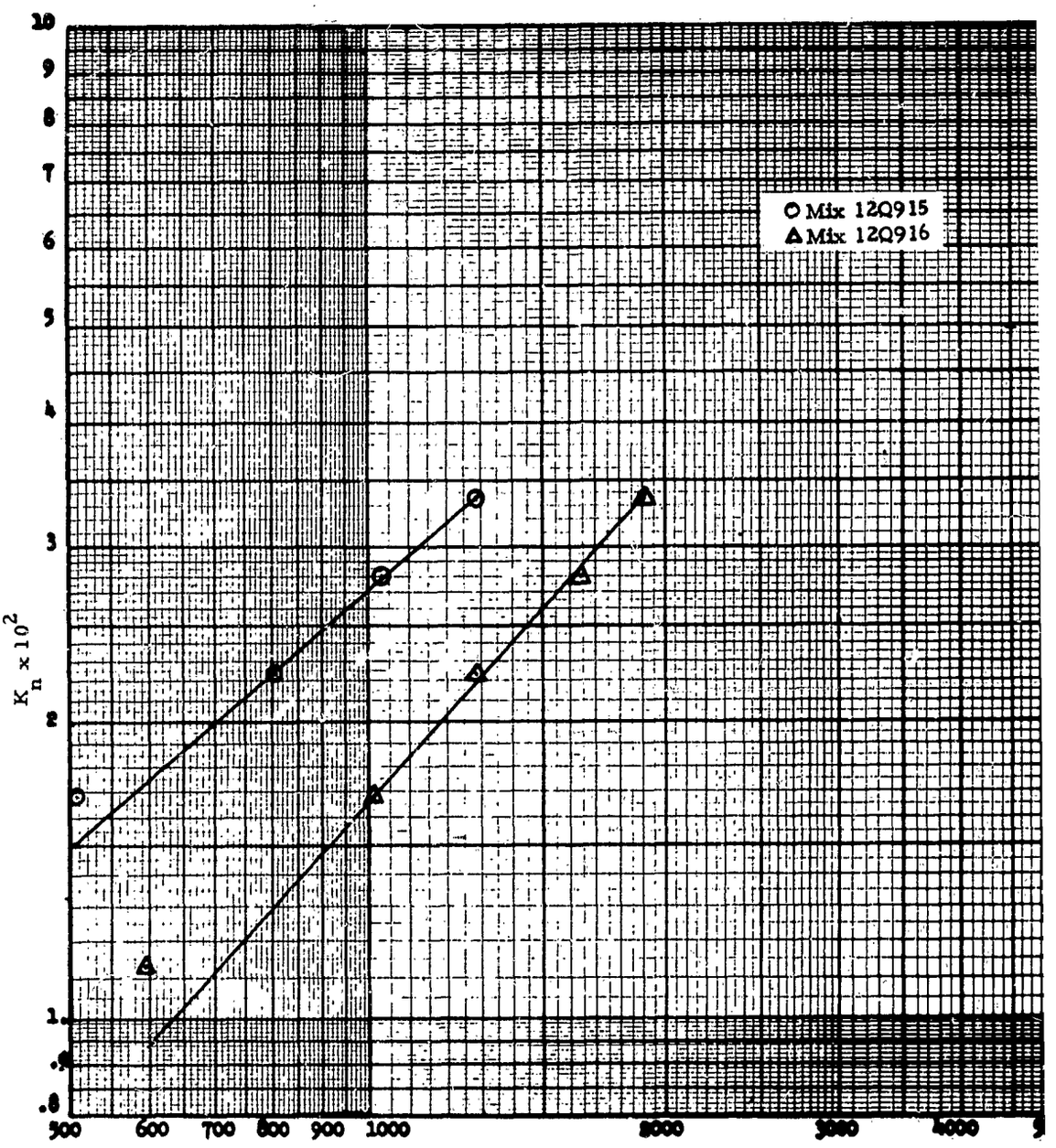


Figure 100. Comparison of K_n Versus Pressure for Mixes 12Q915 and 12Q916

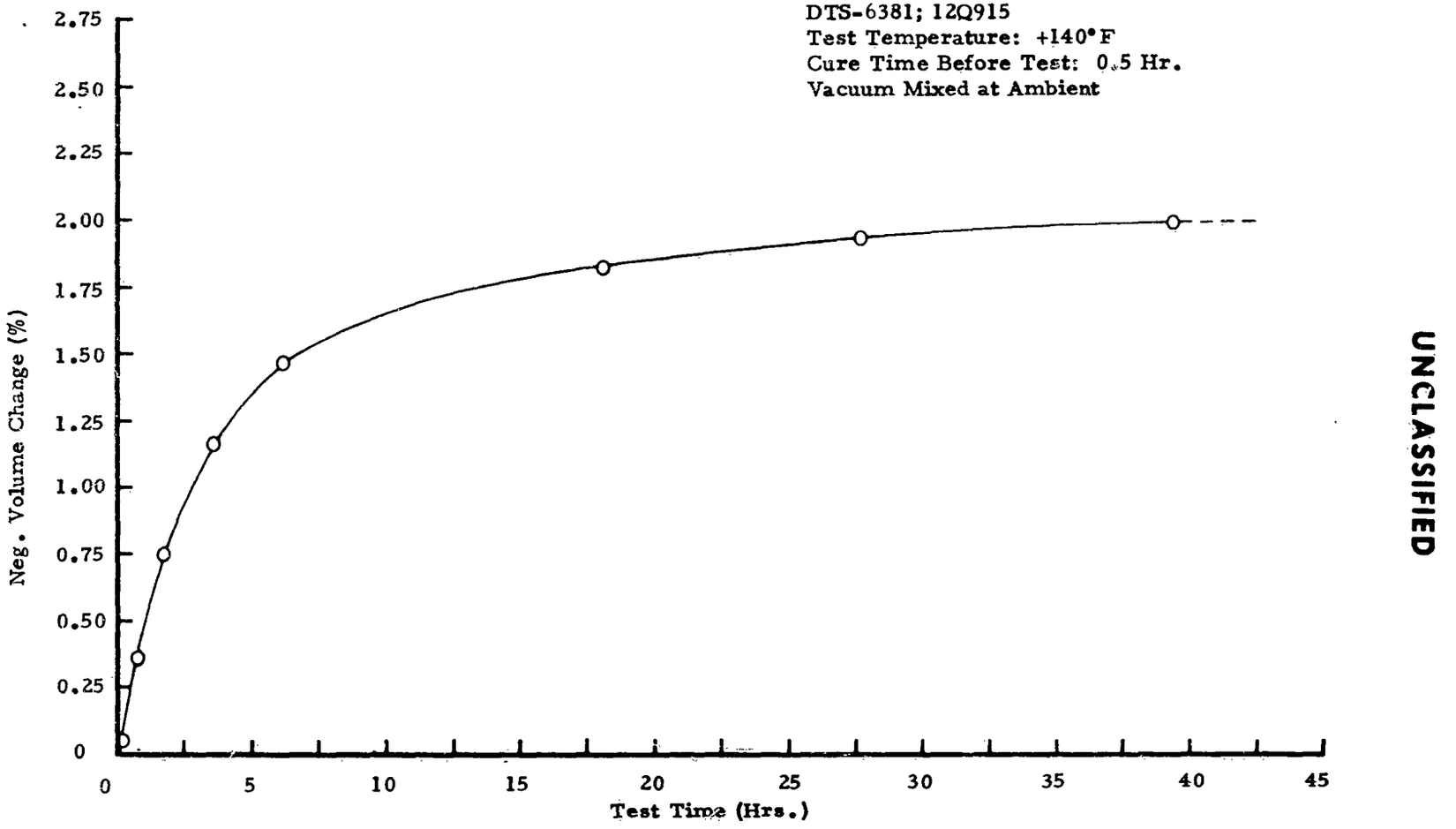


Figure 101. Free Body Volume Change, Mix 12Q915

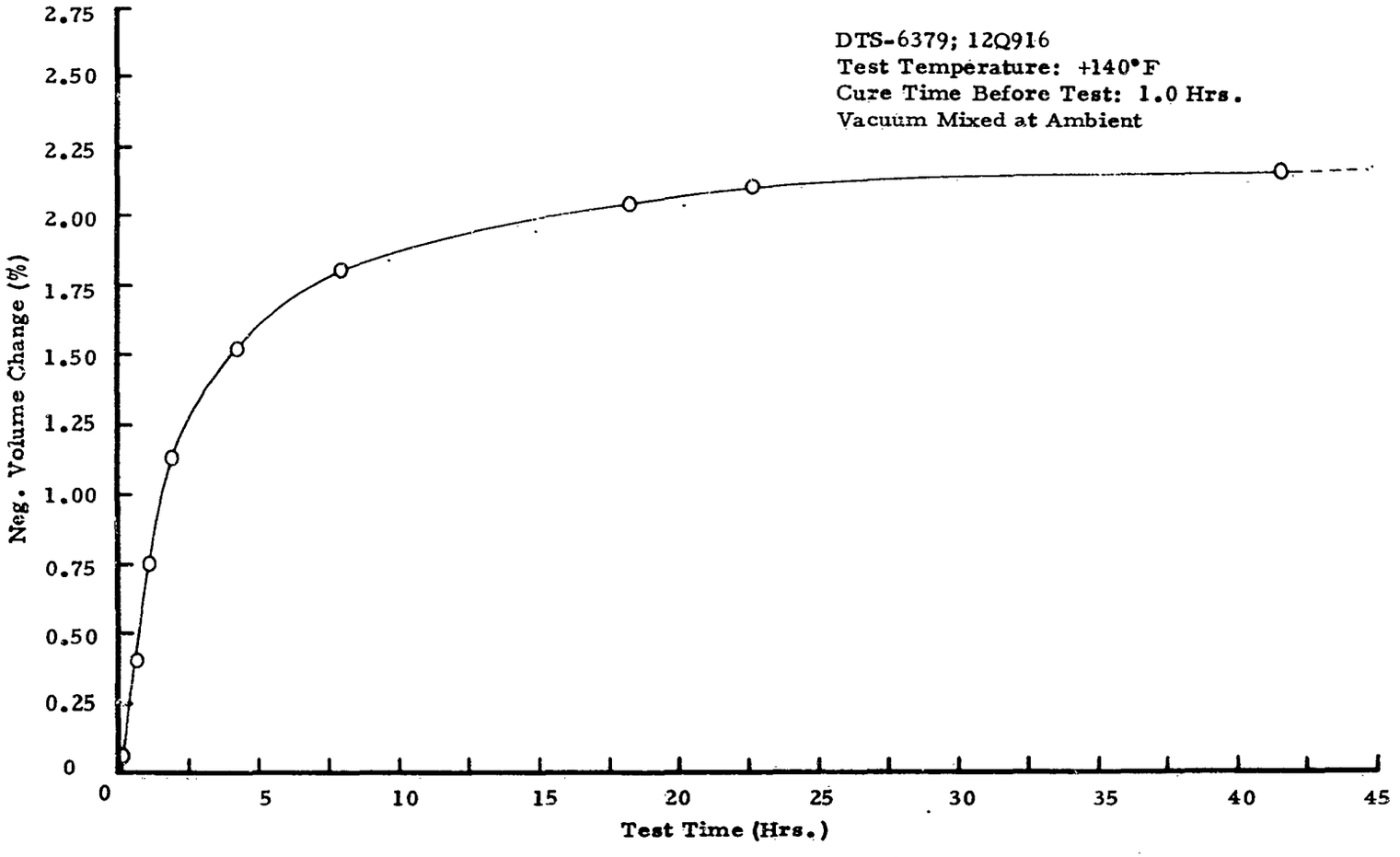


Figure 102. Free Body Volume Change, Mix 12Q916.

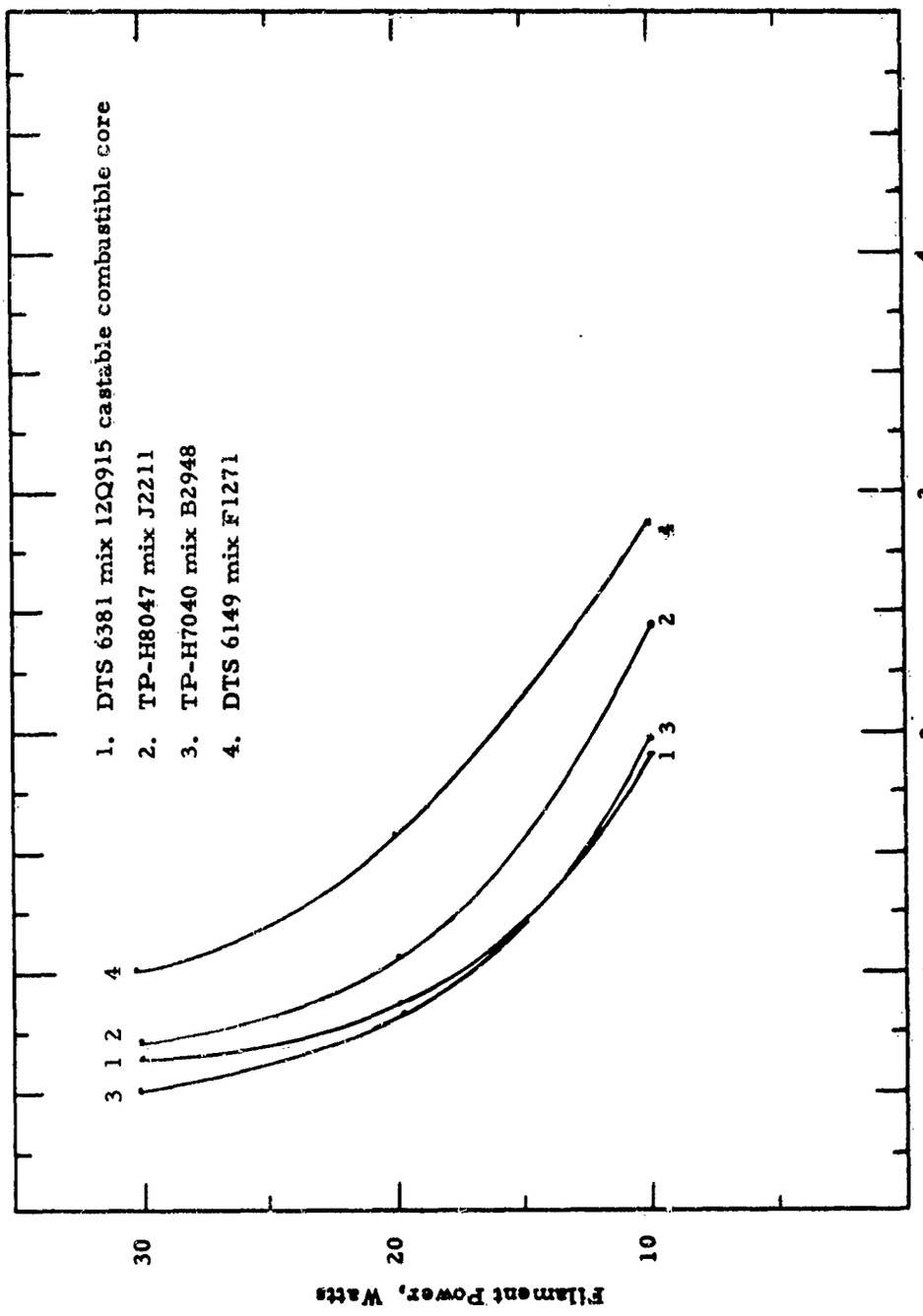


Figure 103. Filament Power versus Propellant Ignition Delay

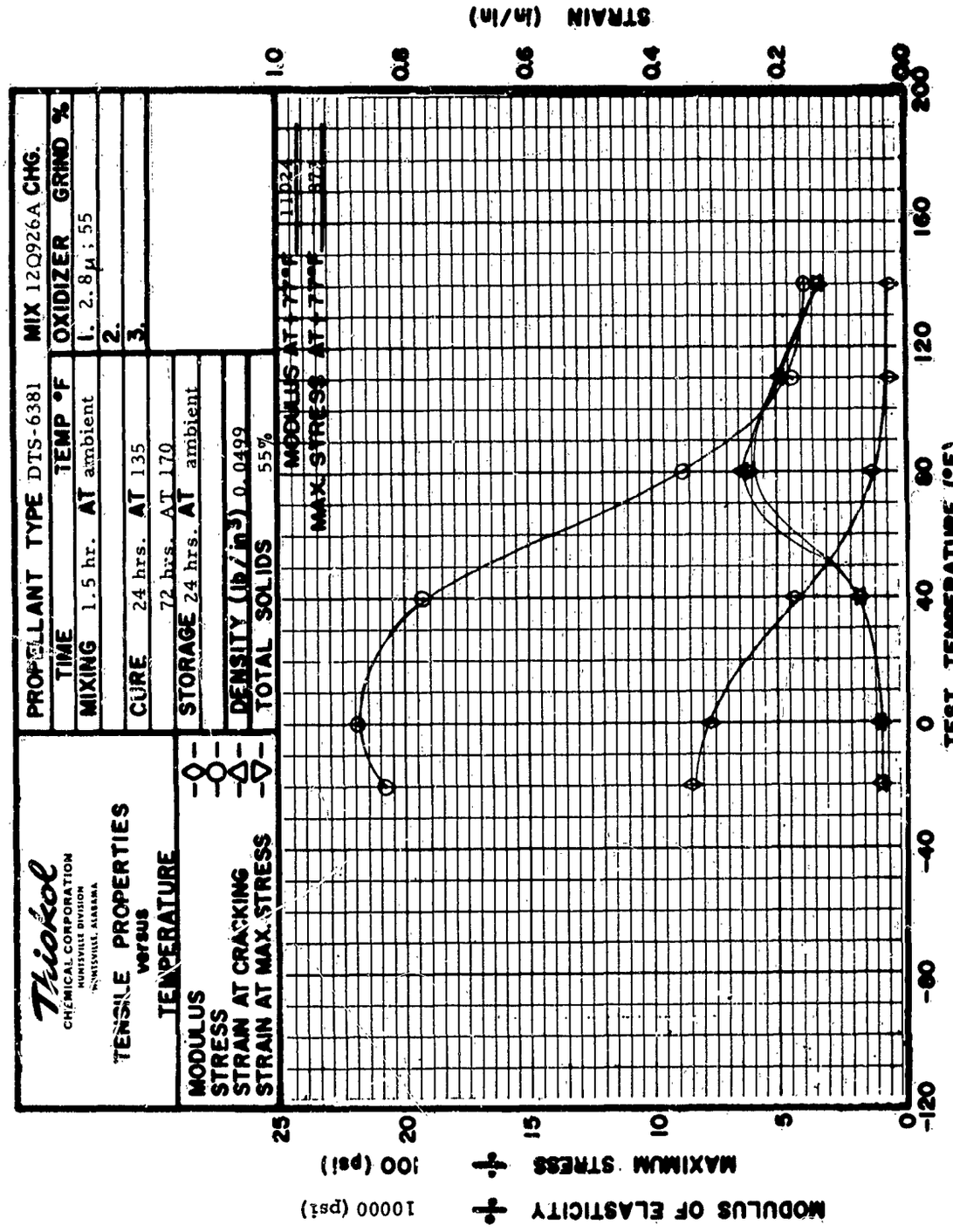


Figure 104. Tensile Properties Versus Temperature, Mix 12Q926A

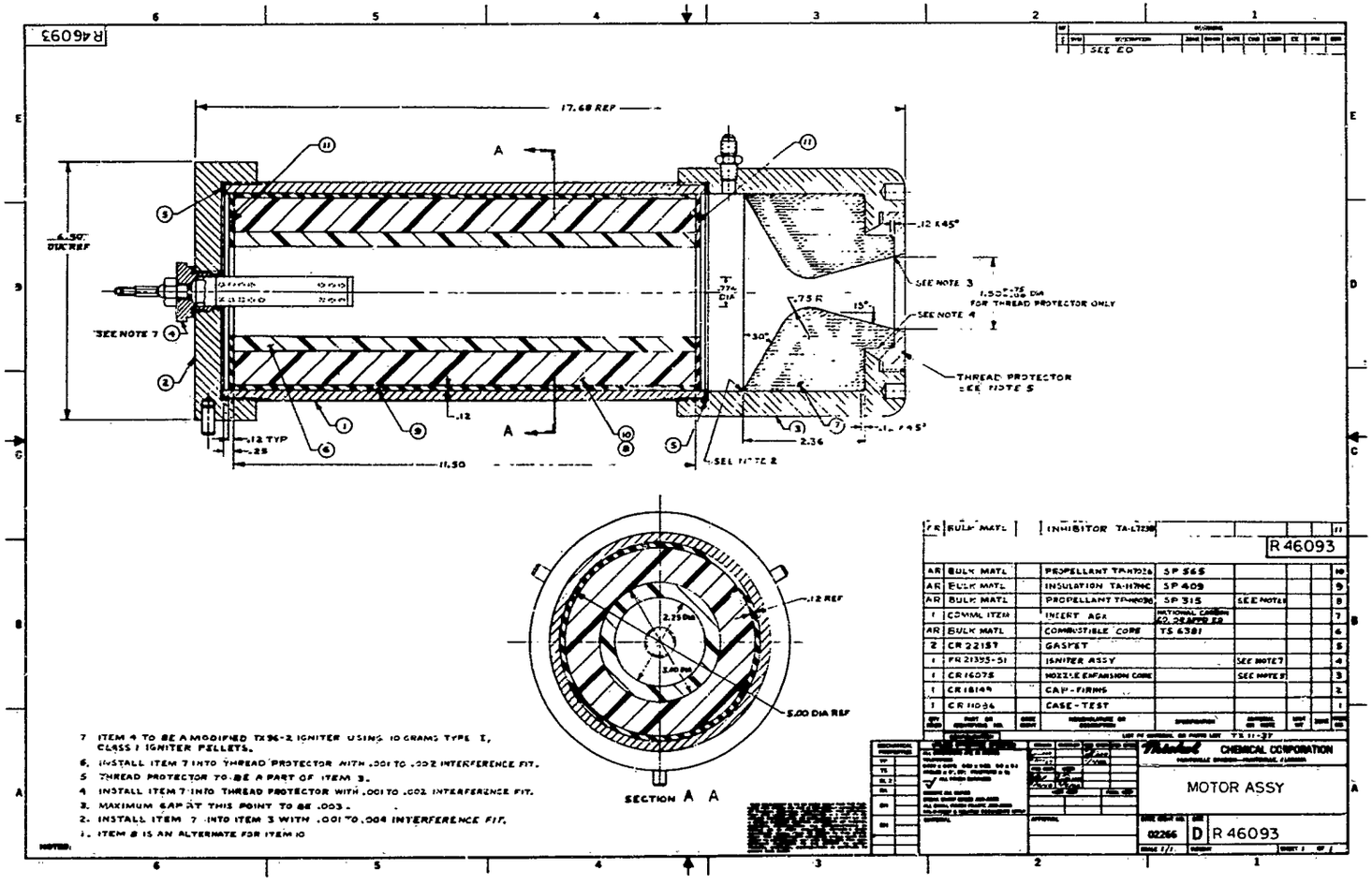


Figure 105. TX11-37 Motor Assembly

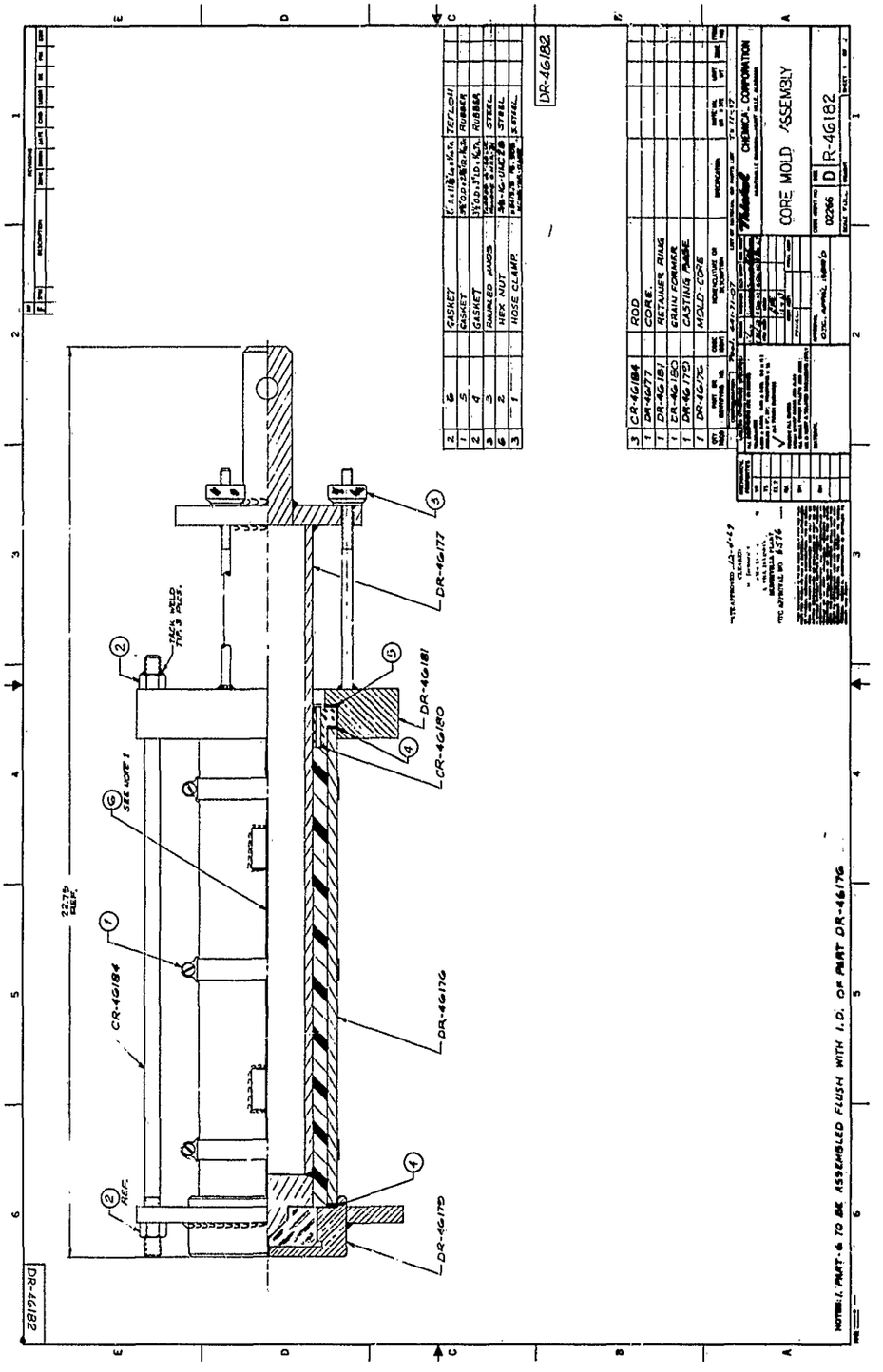


Figure 106. Core Mold Assembly

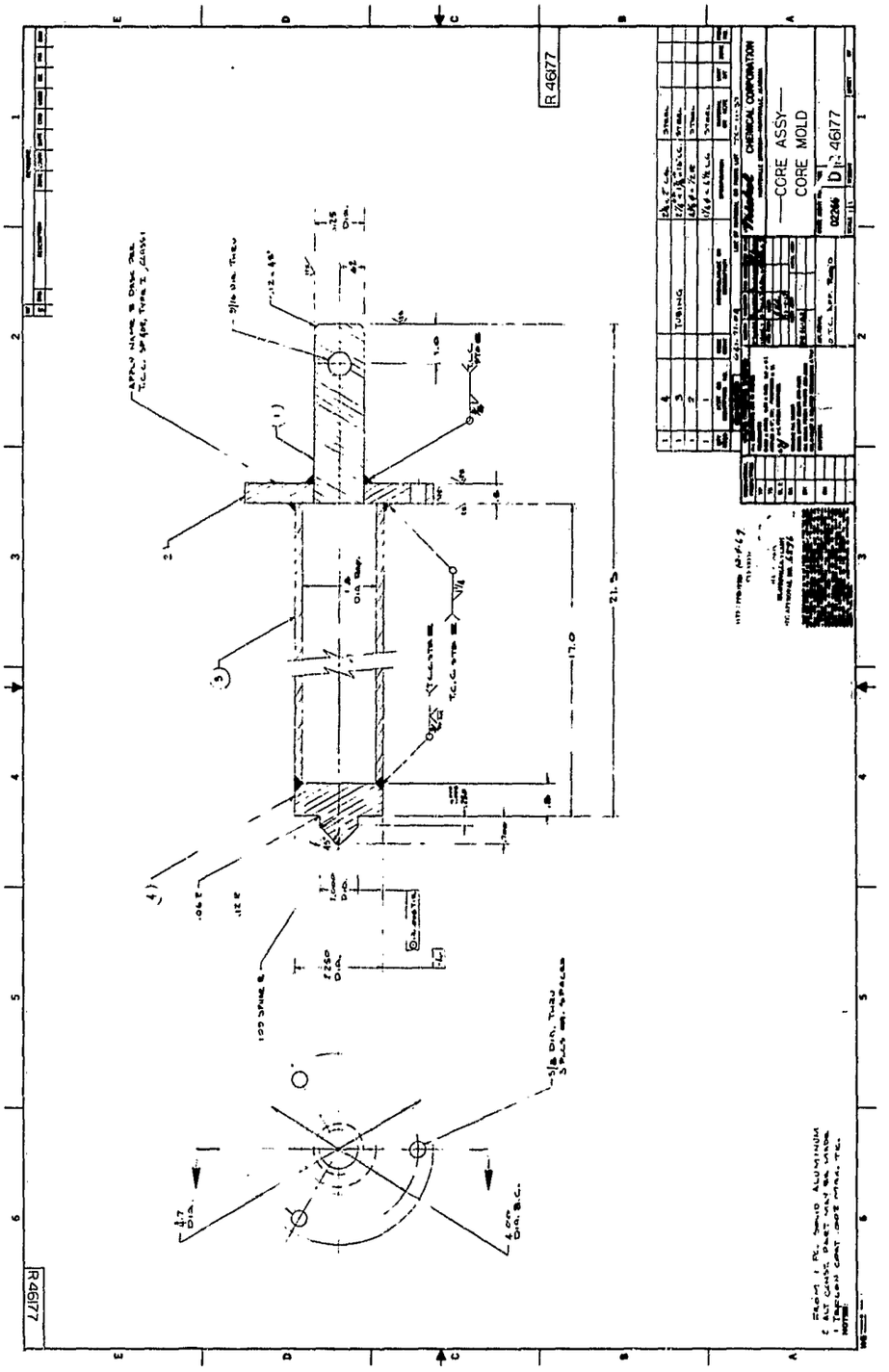


Figure 107. Core Assembly - Core Mold

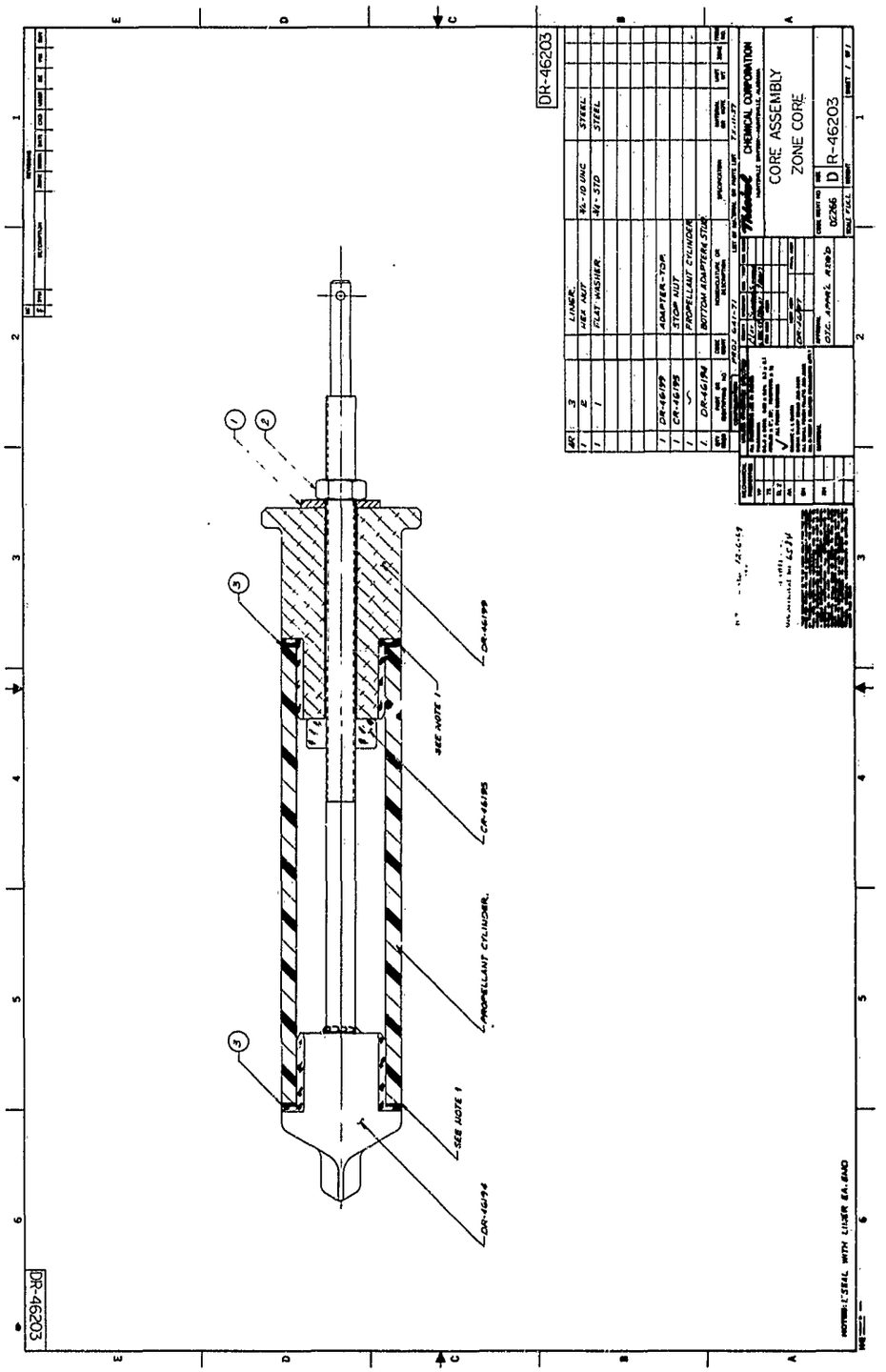


Figure 108. Core Assembly

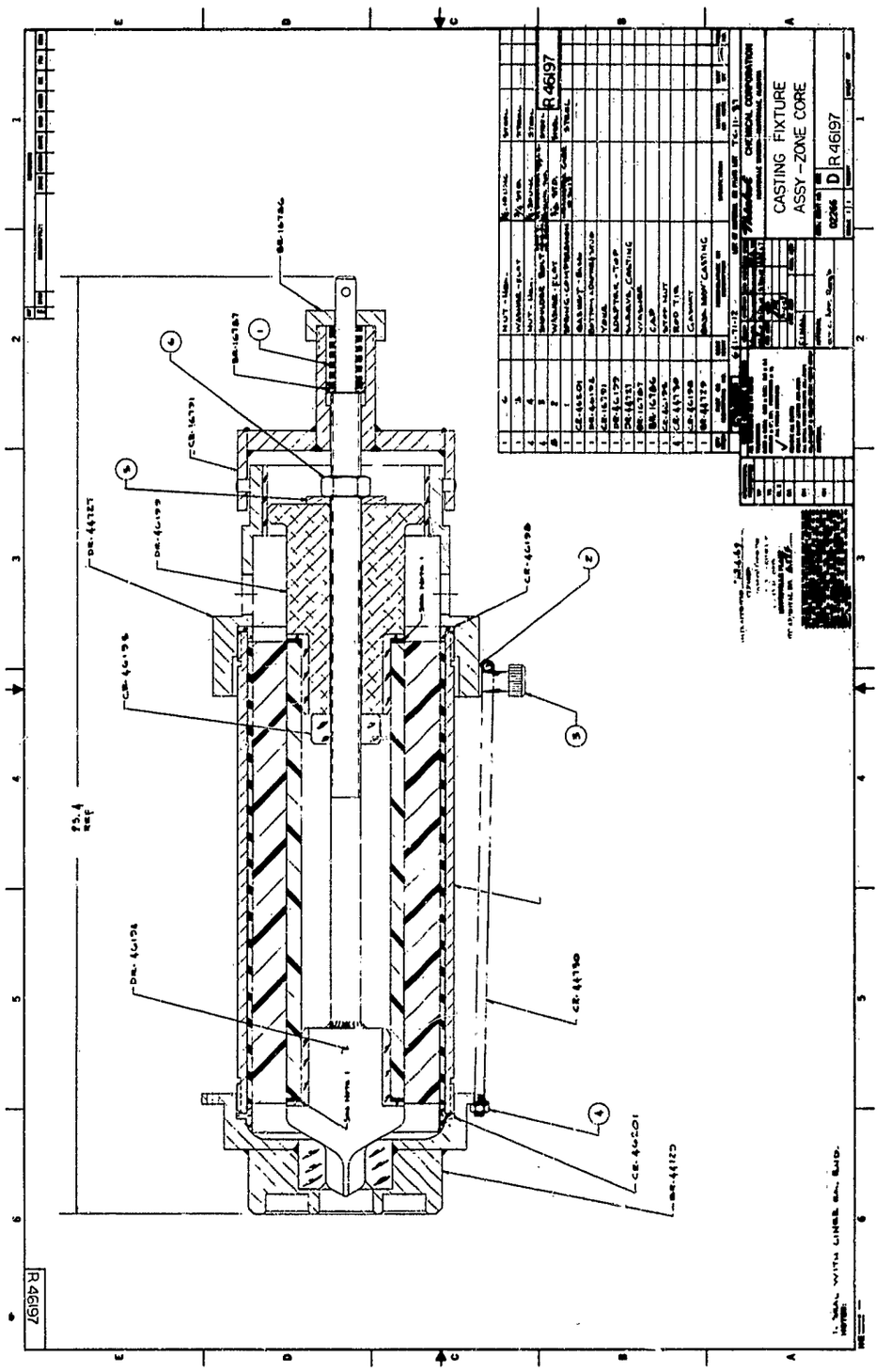


Figure 109. Casting Fixture Assembly

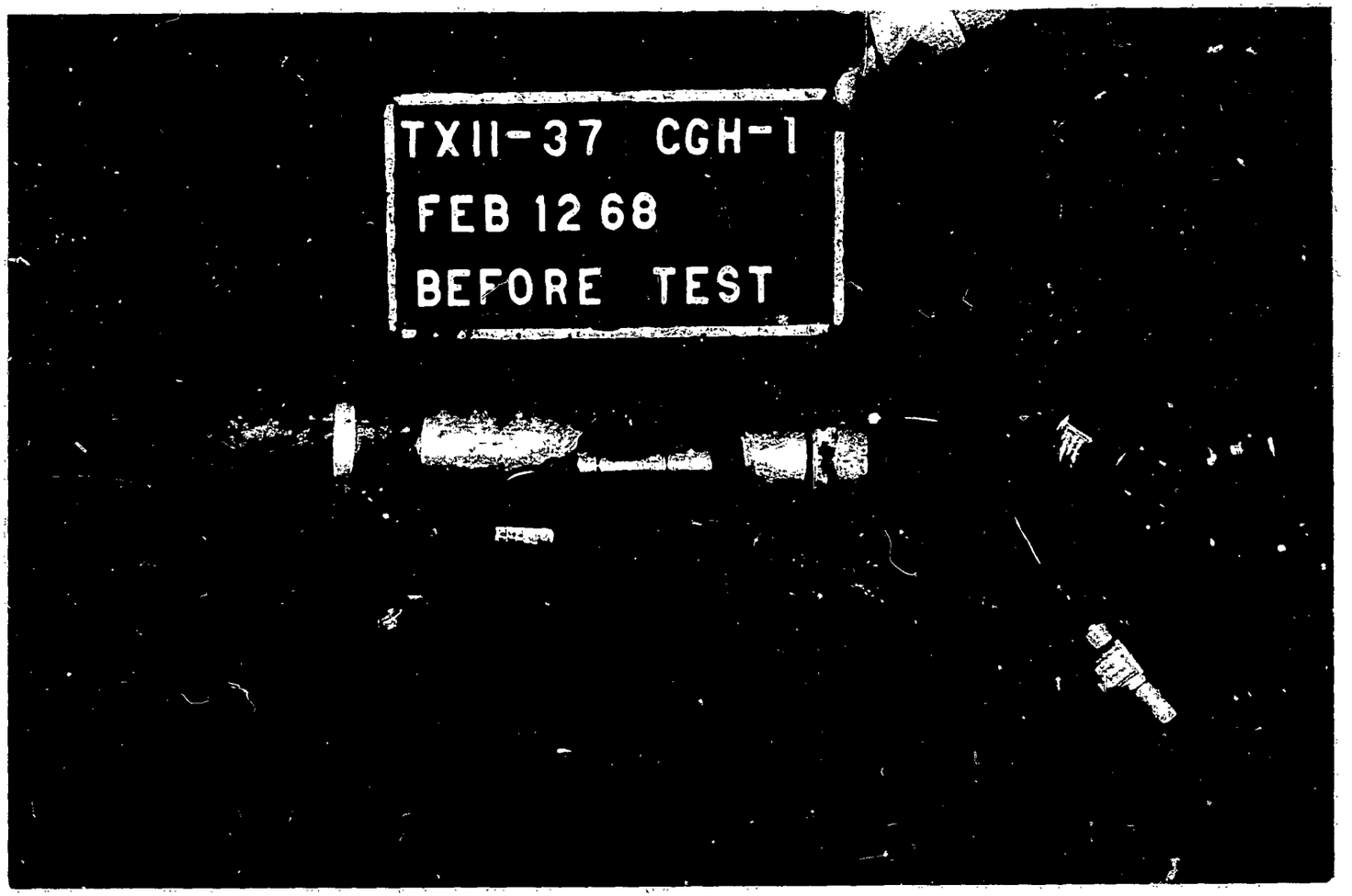


Figure 110. Photograph of TX11-37 Motor No. 1 Before Static Test

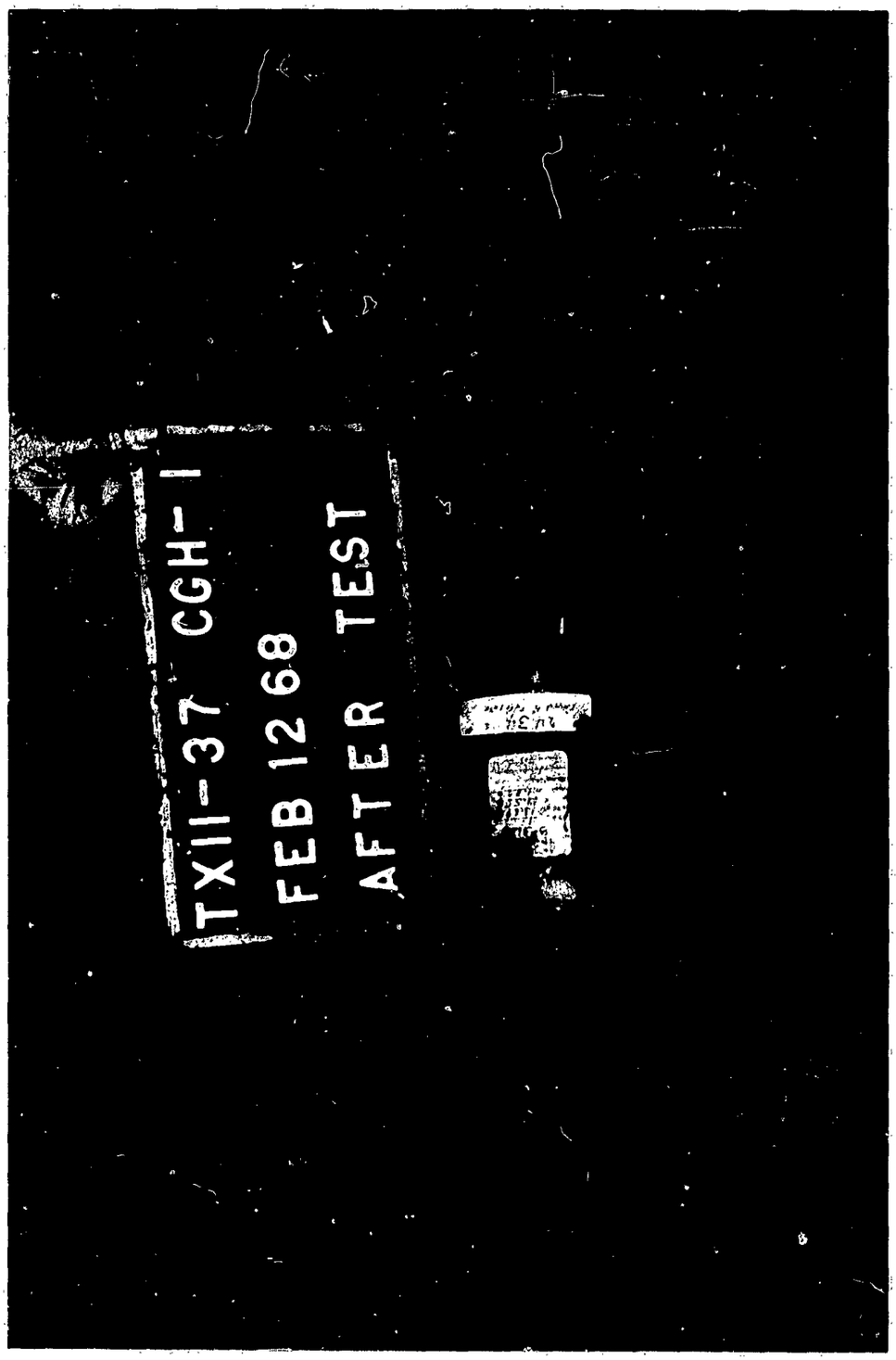


Figure 111. Photograph of TX11-37 Motor No. 1 After Static Test

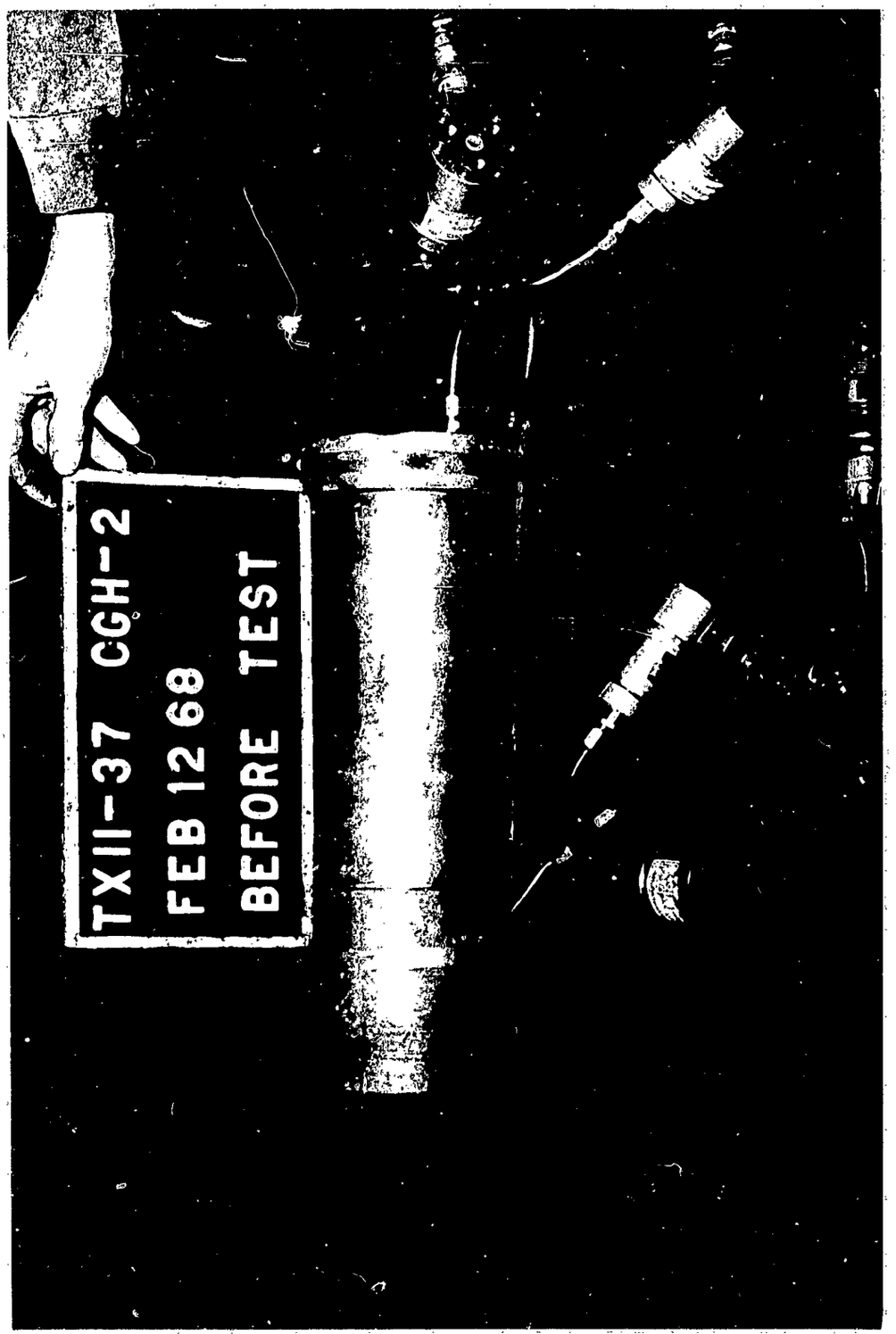


Figure 112. Photograph of TXII-37 Motor No. 2 Before Static Test

Figure 113. Photograph of TX11-37 Motor No. 2 After Static Test

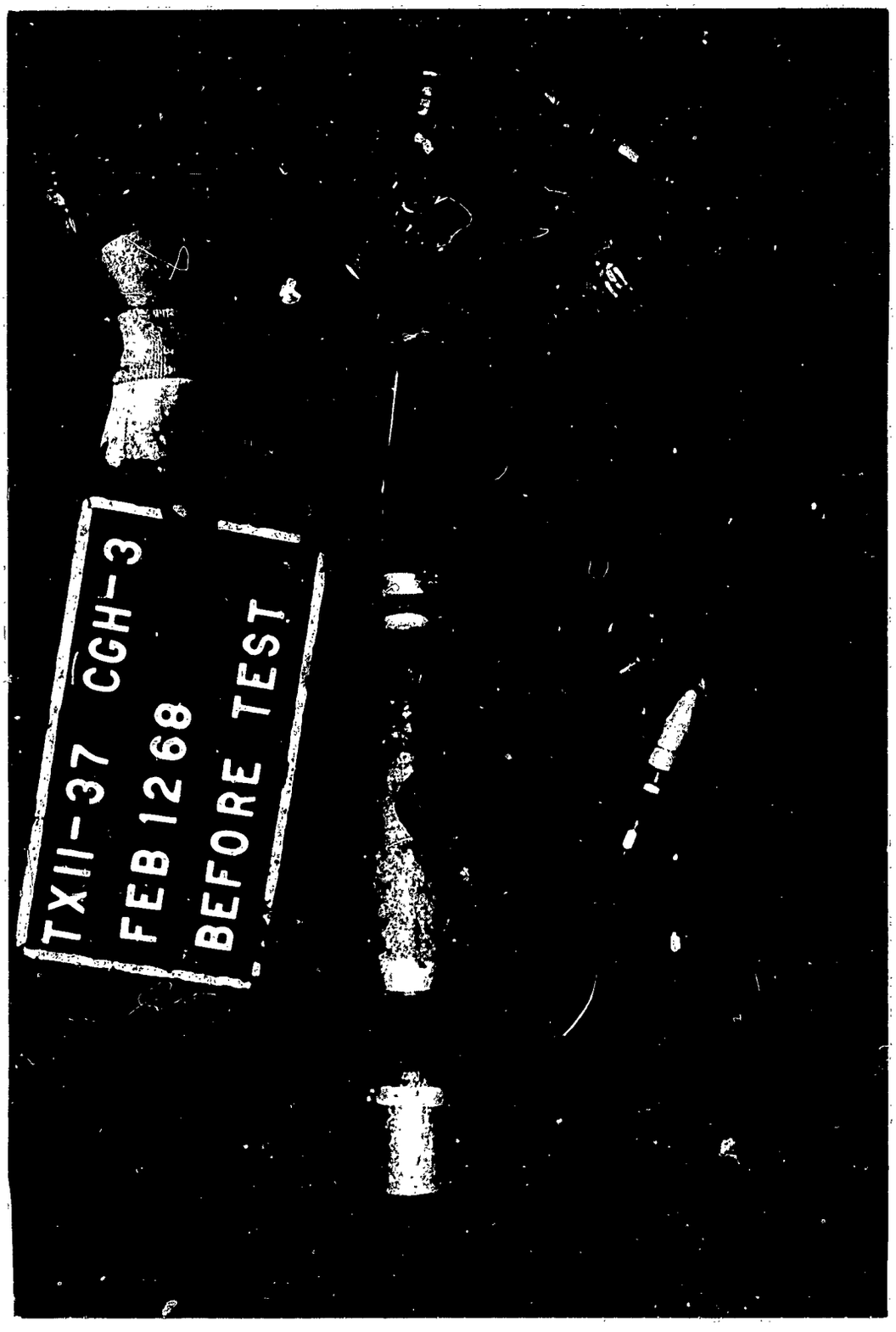


Figure 114. Photograph of TX11-37 Motor No. 3 Before Static Test

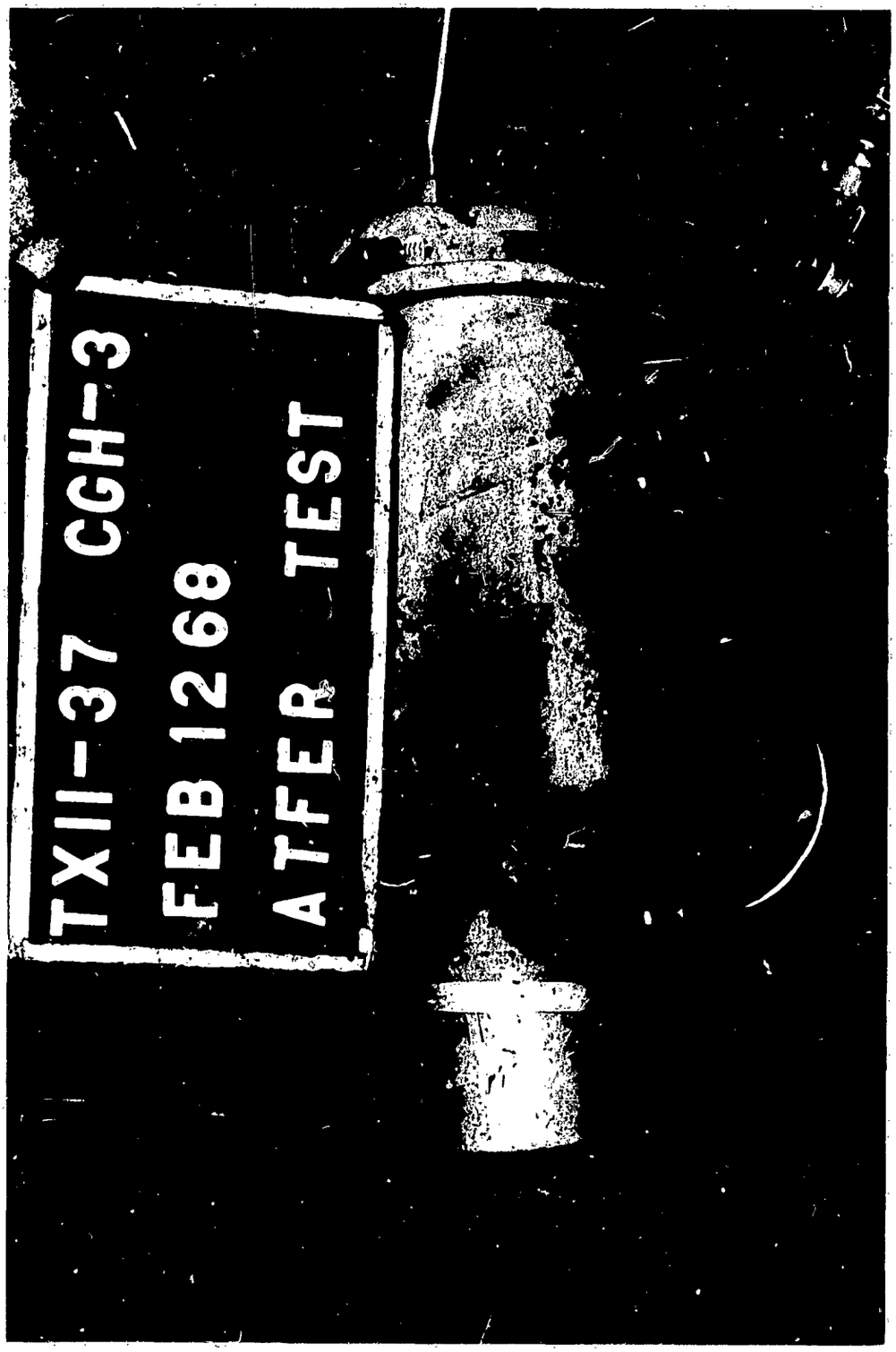


Figure 115. Photograph of TX11-37 Motor No. 3 After Static Test

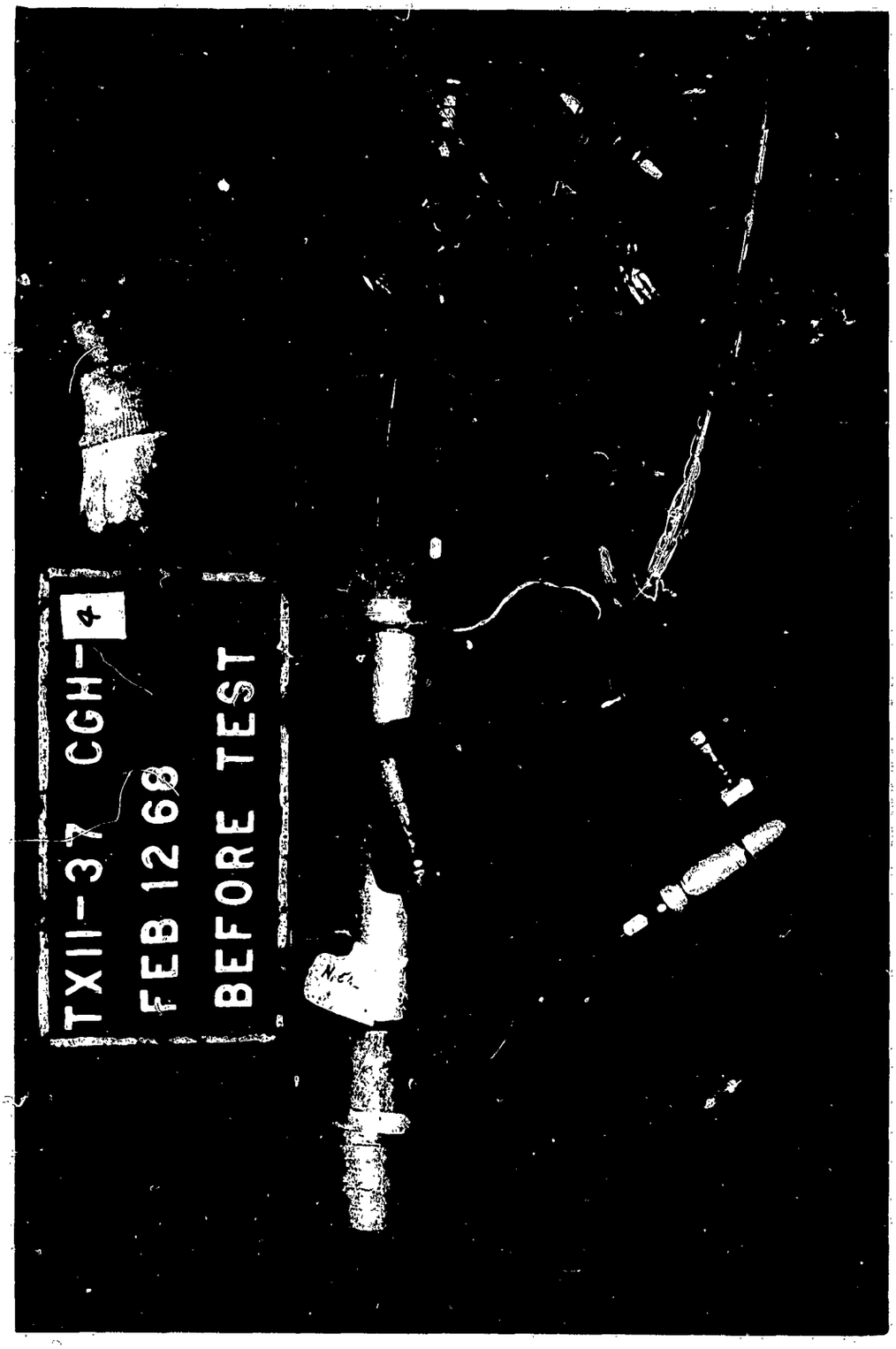


Figure 116. Photograph of TX11-37 Motor No. 4 Before Static Test

Figure 117. Photograph of TXII-37 Motor No. 4 After Static Test

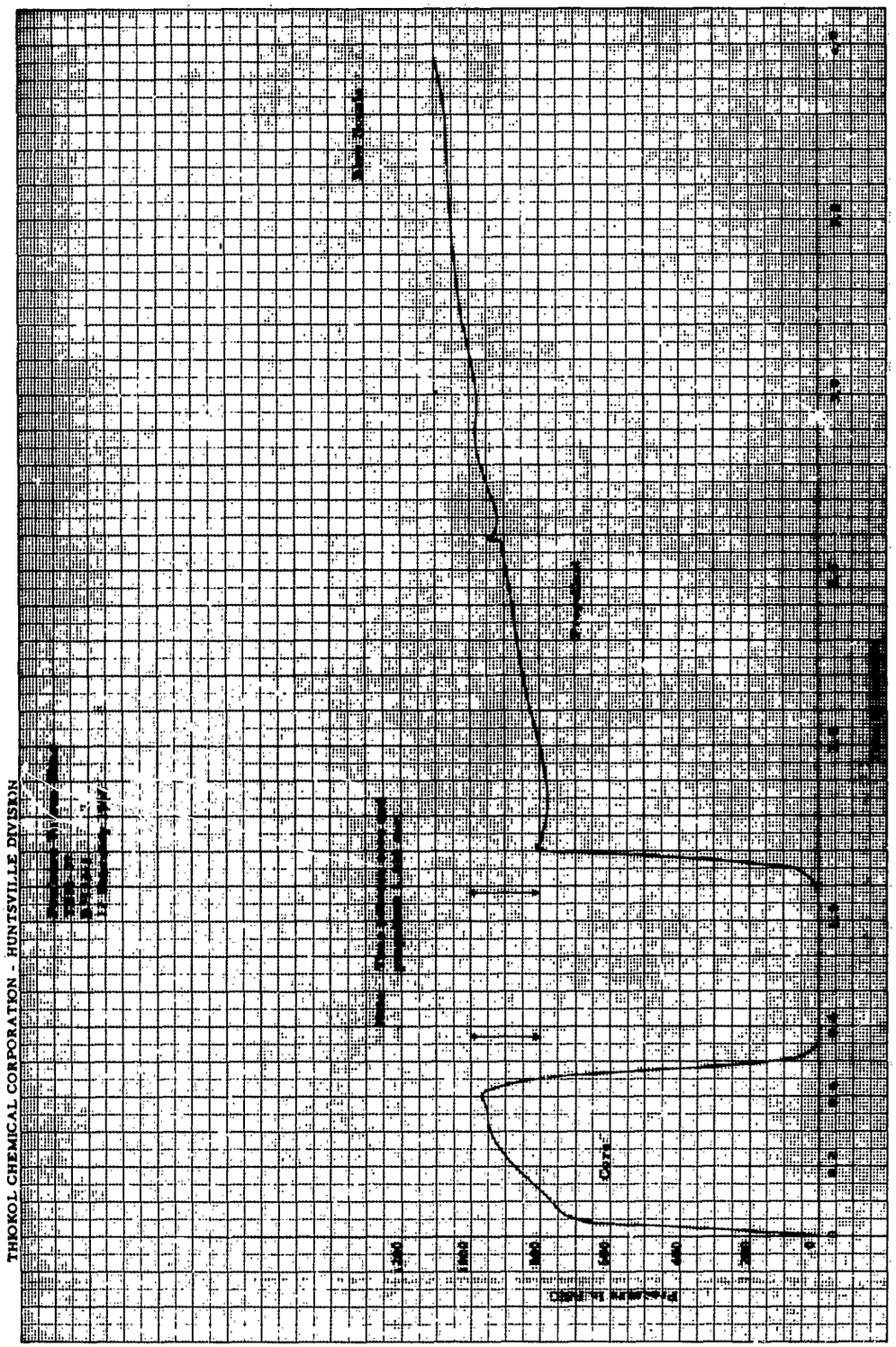


Figure 118. Pressure versus Time Trace, TX11-37 Motor No. 1

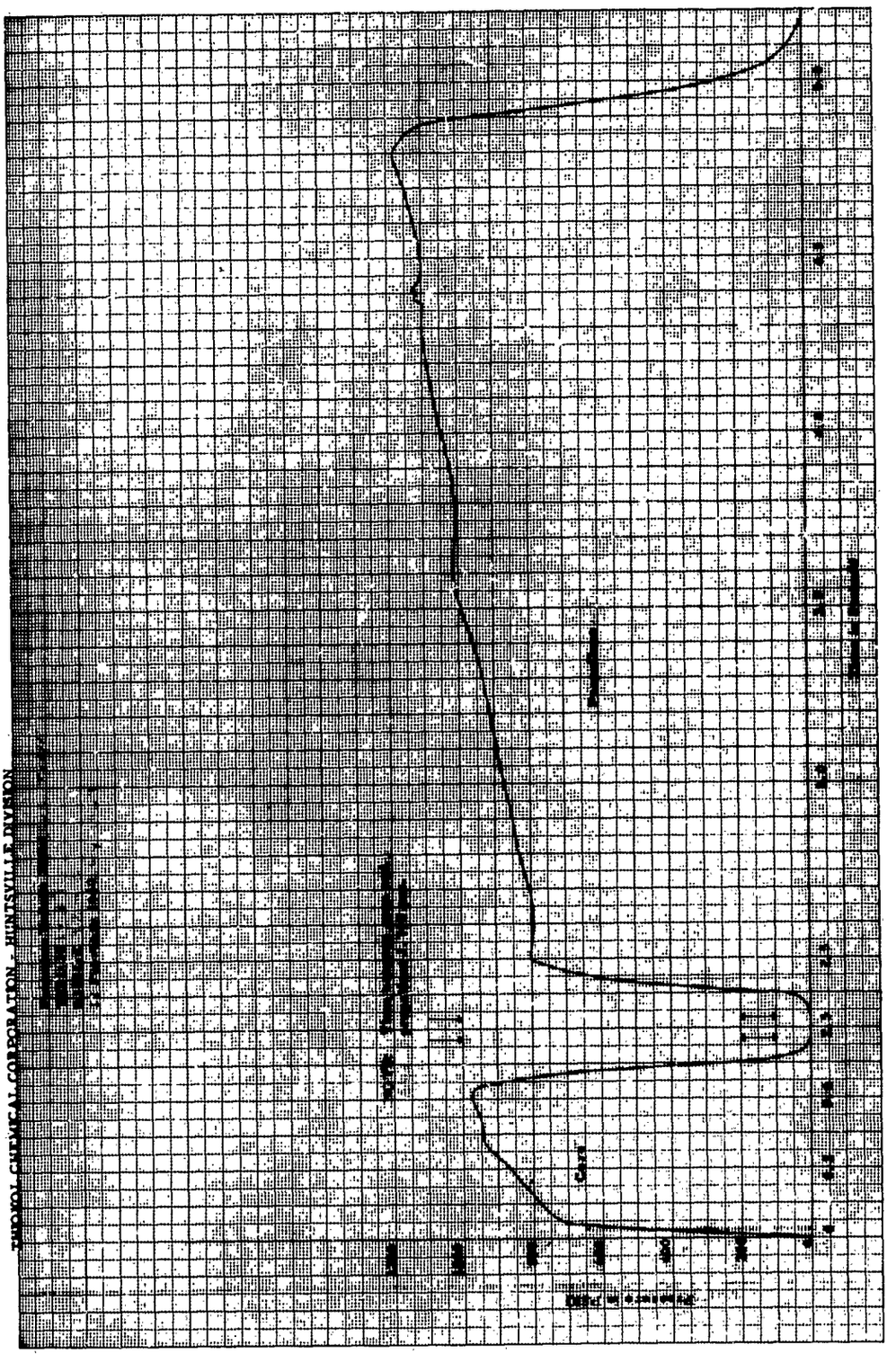


Figure 119. Pressure versus Time Trace, TX11-37 Motor No. 2

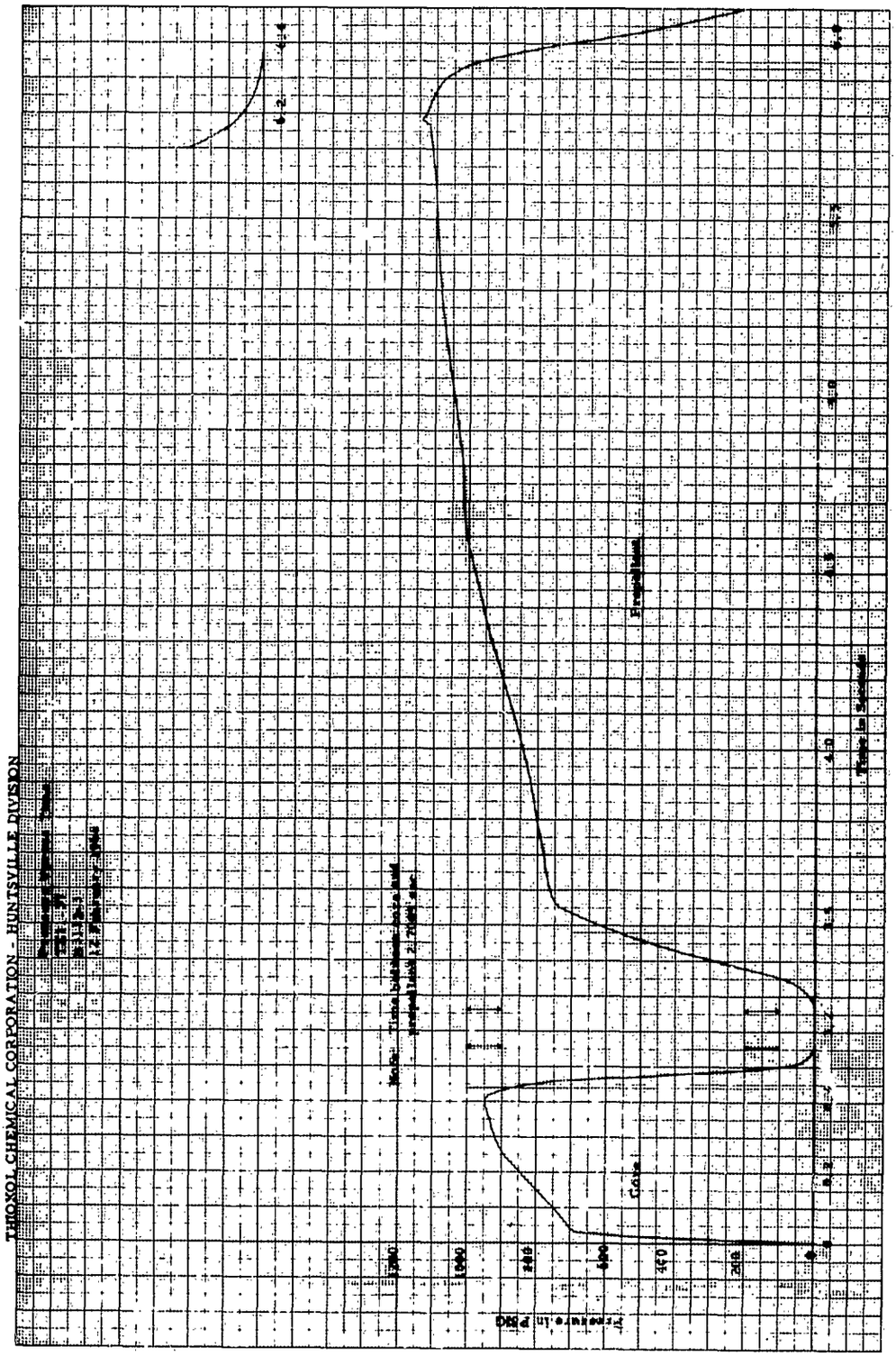


Figure 120. Pressure versus Time Trace, TX11-37 Motor No. 3

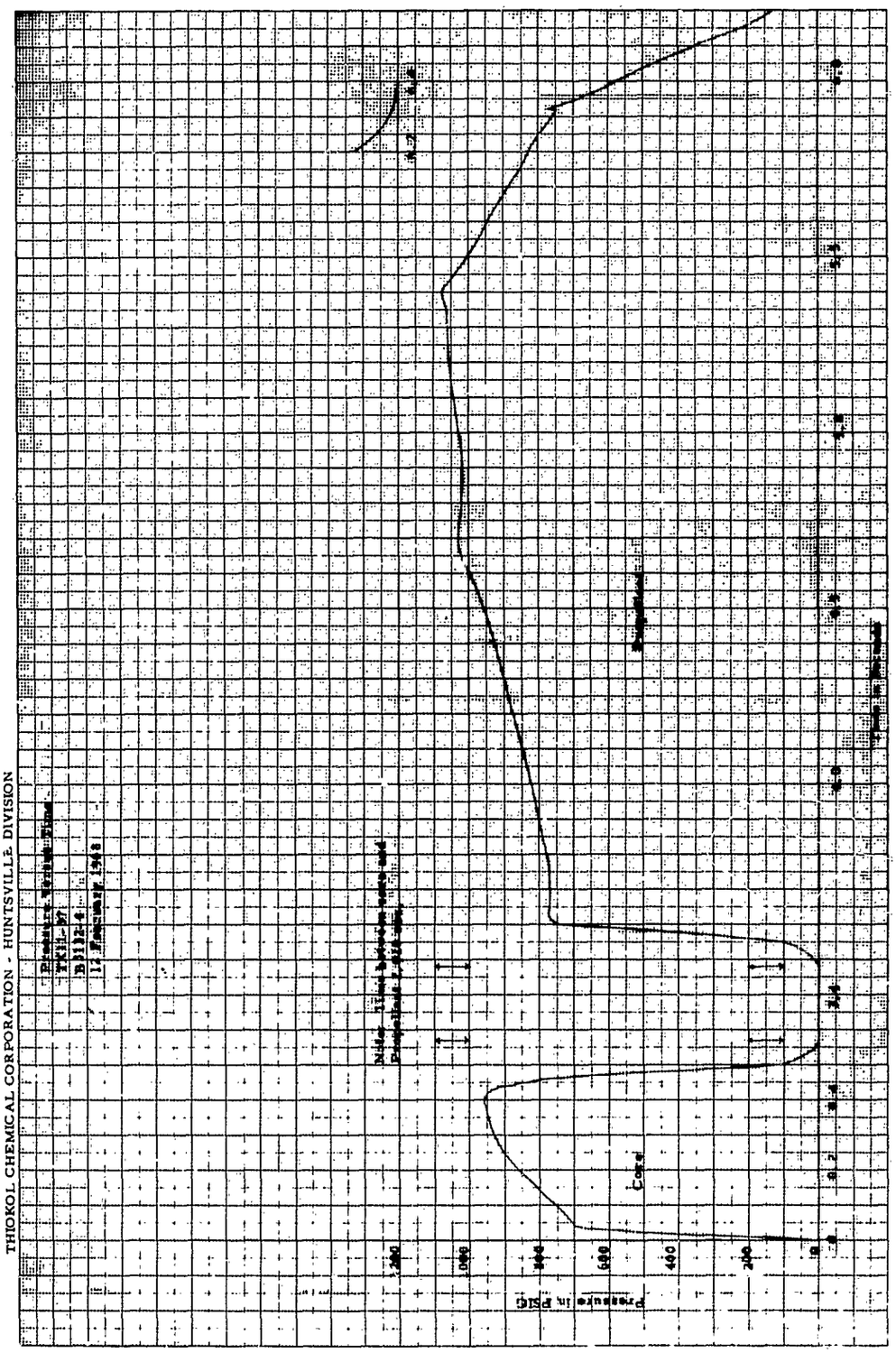


Figure 121. Pressure versus Time Trace, TX11-37 Motor No. 4

APPENDIX A

MEMBRANE CORE

BILL OF MATERIALS FOR CONTROL SYSTEM

Item	Quantity	Material Cost	Service Fluid	Remarks
8" 150# Gate Valves	3		Fluid	
8" 150# Globe Valve	1			
4" 150# Gate Valve	6			
4" 150# Globe Valve	1			
8" x 4" x 8" Tees (STL)	5		Fluid	
8" x 6" x8" Tee (STL)	1		Steam & Water	
4" x 4" x 4" Tees (STL)	1		Fluid	
8" 90° ELL	4			
4" 90° ELL	4			
8" 150# Flanges	18			
4" 150# Flanges	24			
8" Rubber Gaskets	18			
4" Rubber Gaskets	24		Fluid	
4" 300# Gate Valve	1		Steam	
(4" Reg. Valve (w) Thermostat Control)	1		Steam	Robert Shaw - Fulton Type 1009 - B1
6" Globe Valve	1		Water	
8" Sch. 40 STL Pipe	160'		Fluid	
8" 150# Rubber Hose	25'		Fluid	
4" Sch. 40 STL Pipe	240'		Fluid & Steam	
6" Sch. 40 Pipe (STL)	100'		Water & Cond.	
6" 150# Flanges	4		Water	
2000 GPM Pump at 175'	1		Fluid	
50 GPM Pump at 50'	1		Fluid	
4" Flow Control Valve	1		Fluid	Robert Shaw - Fulton Type 1230
3000 Gal. Tank	1	$3200 (est)	Fluid	
20" Dia., 2 Pass, Heat Exchanger	1	$2700 (est)	Fluid	(American Std. C-200)
Dial Thermometers	4		Fluid	(Marsh) 0-250°F
(50 Hp Motor for 2000 GPM Pump)	1		Elect.	440 V. (3 ph)
(Motor Controller for 50 Hp Motor)	1		Elect.	West. Type Y3JNNC (440 V)
Pushbutton Station			Elect.	

A-2

Item	Quantity	Material Cost	Service Fluid	Remarks
(Motor Controller for 1 HP Motor)	1		Elect.	West. Type Y1FNNC (440 V)
(1 HP Motor for 50 GPM Pump	1		Elect.	(440 V) (3 ph)
Pushbutton Station	1		Elect.	
Float Switch	1		Elect.	Robert Shaw - Fulton Type SL-501
#3 Elect Gable	400'		Elect.	
#12 Elect Cable	400'		Elect.	
Concrete Found.	4 yds^3			
8" Pipe Supports	10			
4" Pipe Supports	10'			
4" 150# Rubber Hose	10			
Promixity Switch	1			Minn. Honeywell # 163A
Panel Alarm	1			
Control Panel	1			
110 V Disconnect Switch	1			

CASTING FIXTURE

Item	Quantity	Design - Ex.	Design - Non-ex.	Fabrication
Adapter	1	12	12	
Center Post	1	12	12	
Holdown Bar	1	12	12	
Valley Segments (Core)	6	16	8	
Star Segment (R.H.)	6	16	8	
Star Segments (LH)	6	16	8	
Boot with Mold	1	40	32	
Membrane	1			
Lock-Ring	1	4	4	
6" O-Ring	1			
14" O-Ring	1			
Tool Column 10' lgs.	10	24	24	
Follower (Al	1	40	24	
Ball Bushing)	4			12" Dia. Thomson
Aft Support	1	32	24	
Hydraulic Jack	1			Blackhawk Type RC60 (w) P-84 Pump
Jack Adapter	1	8	8	
Alignment Lug	6	8	8	
Clamp Strip	1	24	12	
Magnet	1			
Cable lengths 10' lg.	10	32	16	
(Adapter Cable to Casting Elevation)	1	32	32	

A-4

Item	Quantity
(Air Line Elevator Control 10' Lengths)	10
(Adapter - Air Line to Casting Elevator)	1
Bolts and Nuts	
Soc. Hd. 1" Ø x 3" lg	12
Shd. Bolt 1" Ø x 12" lg.	10
Sock Hd. 3/8Ø x 2" lg.	50
Soc. Hd. 1/2Ø x 2" lg.	60
Hex Hd. 7/8Ø x 4-1/2 lg.	220
Hex Hd. 5/8Ø x 3-1/2 lg.	200
Hex Hd. 3/4Ø x 3-3/4 lg.	60
(Misc. & Contingency) 10%	
Aft Motor Closure	1
Aft Nozzle Closure	1

APPENDIX B

CALCULATION OF VALUES LIMITING MOTOR THRUST DURING IGNITION TO BE LESS THAN MOTOR WEIGHT

Calculations of limiting values for the various core ballistic parameters are included below. These calculations are based upon the principle that, for equilibrium burning, the weight rate of gas production must equal the weight rate of gas discharged by the motor.

$$\dot{W}_1 = A_s\, r_b\, \rho \text{ (weight rate gas production)} \qquad (1)$$

$$\dot{W}_2 = \frac{P_c A_t g}{c^*} \text{ (weight rate gas discharge)} \qquad (2)$$

where:

W = Weight rate of flow

A_s = Average burning surface

r_b = Propellant burning rate

ρ = Density of the propellant

P_c = Average chamber pressure

A_t = Nozzle throat area

g = Acceleration of gravity

c^* = characteristic velocity

Setting (1) equal to (2) it can be shown that $\frac{P_c}{r_b} = \frac{c^*}{g}\,\frac{A_s}{A_t}$ (3) (equilibrium relations)

Equation (3) must be satisfied for the motor to operate stably. For the 156-inch diameter motor, elements of equation (3) can be assigned limiting values. These are:

A_s = 397,675 in^2

A_t = 2,974 in^2

P_c = 208 psia, F 903,000 lbs.

Making the assumption that these conditions exist during ignition, then a limiting equation can be written for the combustible core material:

$$g\,\frac{P_c A_t}{A_s} \geq r_b\, c^*\, \rho \qquad (4)$$

where all items in the left hand of the equation are fixed values and those in the right hand side of the equation are only limited in that the product of the core material ballistic properties must satisfy equation (4). This product then establishes only an upper limit on its value and allows as much freedom as possible in the selection of a core material. With the selected fixed values, equation (4) becomes:

$$r_b c^* \rho \leq 49.93$$

This limits motor thrust during ignition to be less than motor weight.

APPENDIX C

ANALYSIS OF COMBUSTIBLE CORE MATERIAL PROPERTY REQUIREMENTS

Stresses and strains are imposed on the propellant and core material as a result of differential thermal expansion between the propellant, core material and motor case. Since the propellant must remain bonded to the case, the surface of the propellant moves toward the case wall when the temperature is lowered. If the core were unbonded, the core would move radially inward. However, since the core is bonded to the propellant, the core must move outward with the propellant. Consequently, stresses and strains are imposed upon the propellant grain.

The variables which affect the magnitude of the stresses and strains imposed on the propellant grain include the core thickness, core modulus and the coefficient of thermal expansion of the core material. The allowable stresses and strains are dependent upon the strength of the propellant-to-core bond and the stress and strain capacity of the propellant. Since no information was available on the propellant-to-core bond strength, it was assumed that the allowable core material properties would be governed by the failure characteristics of the propellant. Furthermore, it was assumed that the grain configuration and propellant would be similar to that of the 156-inch diameter motor manufactured by Thiokol Chemical Corporation.

Method of Analysis

For the purpose of this study, the so called "finite element" method of analysis was used to determine the stress and strain distribution in the combustible core and the propellant. This method involves idealizing the continuum by an assemblage of finite-sized elements, for which relationships between corner point forces and displacements are known. The elements are assembled to constitute an analytical model of the structure by joining all elements at their respective juncture points, applying in the process the requirements of equilibrium and compatibility at the juncture points. A more detailed description of the method of analysis and the computer programs was described by Becker[1].

Results and Conclusions

The following conditions were investigated to determine the effects of core material thickness and properties upon induced stresses and strains in the propellant grain.

Core thickness = 0.5 inches, $\epsilon = 2.0 \times 10^{-5}$

(1) E = 2,000 psi (2) E = 20,000 psi (3) E = 200,000 psi

Core thickness = 1.0 inches, $\epsilon = 2.0 \times 10^{-5}$

(4) E = 2,000 psi (5) E = 20,000 psi (6) E = 200,000 psi

Core thickness = 2.0 inches, $\epsilon = 2.0 \times 10^{-5}$

(7) E = 2,000 psi (8) E = 20,000 psi (9) E = 200,000 psi

1. Becker, Eric B. and Brisbane, John J., "Application of the Finite Element Method to the Stress Analysis of Solid Propellant Rocket Grains," Rohm & Haas Company, Special Report S-76.

Core thickness = 2.0 inches, E = 200,000

(10) $\alpha = 0.8 \times 10^{-5}$ in/in/°F (11) $\alpha = 2.0 \times 10^{-5}$

(12) $\alpha = 5.0 \times 10^{-5}$ in/in/°F

For each of the above conditions, the following properties were assumed for the propellant.

E = 183 psi (Modulus of elasticity)

γ = 0.499 (Poisson's ratio)

$\alpha = 6.0 \times 10^{-5}$ in/in/°F (Coefficient of thermal expansion)

For each of the above conditions, plots were made of the contours of the maximum strain and the sums of the principal stresses. A typical grain cross section is shown on Figure 1. An enlarged view of the area enclosed by the dashed line on Figure 1 is shown on Figures 2 and 3. These figures show a layout of the grid used for computation purposes and typical contours of the maximum strain and the sum of the principal stresses. From these curves the stress and strain distribution within the propellant was extrapolated to determine the stress and strain at the propellant-to-core bond. The results from these plots are shown on Figures 4 and 5. It can be seen from these figures that the induced stresses and strains are weakly dependent upon the core modulus. It was also determined from problems 10, 11, and 12 that the induced stresses and strains are weakly dependent upon the coefficient of thermal expansion.

Although the scope of this investigation was not sufficient to specify the absolute maxima or minima, the following properties are recommended for target values for a 2.0-inch core thickness.

E = 200,000 psi (maximum)

$\alpha = 5.0 \times 10^{-5}$ in/in/°F (maximum)

elongation = 4.0% (minimum)

tensile stress = 1,500 psi (minimum)

These properties are based on a nominal propellant strain capability of 20% and a design strain of 15%. The sum of the principal stresses were within the stress capability of the propellant and as a result imposed no restrictions on the core material properties.

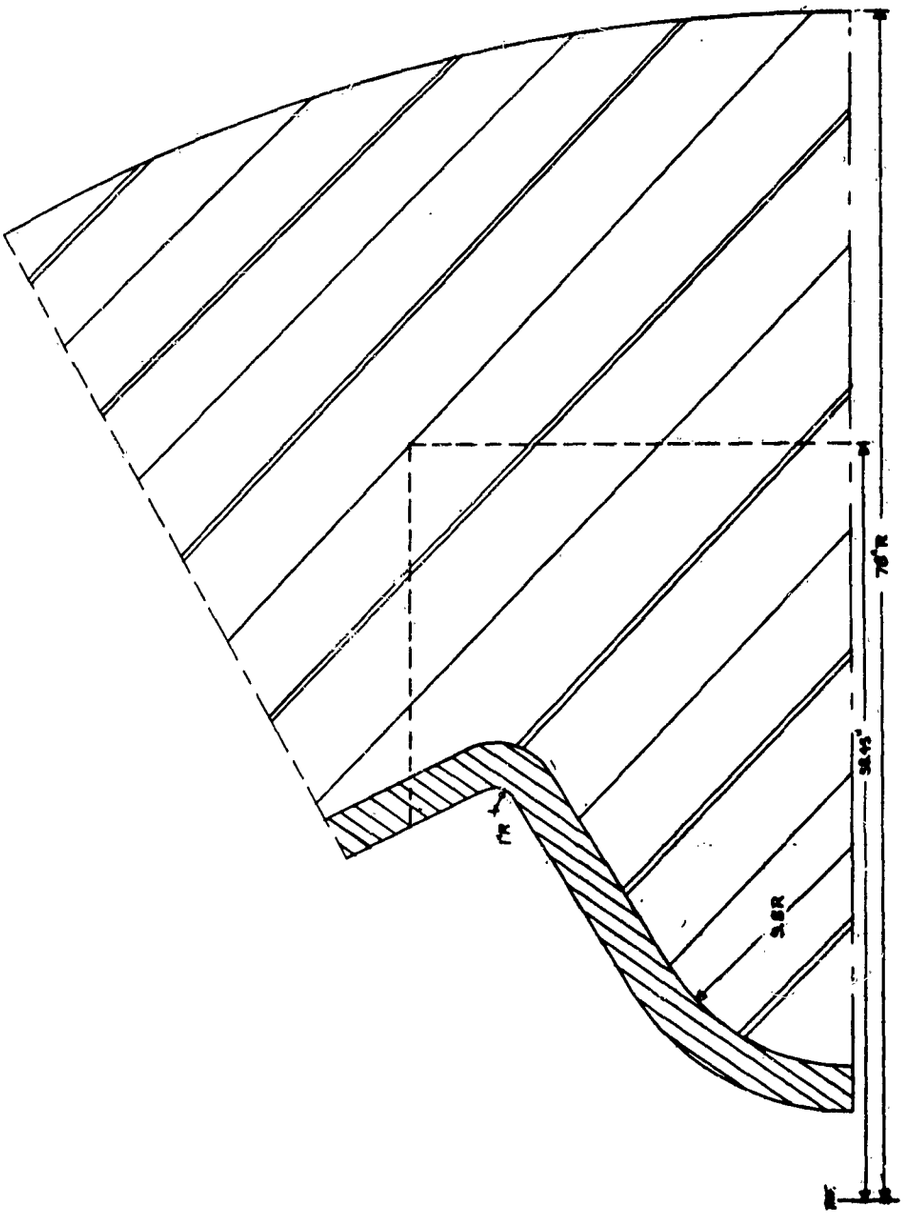


Figure C-1. Segment of Grain Cross Section.

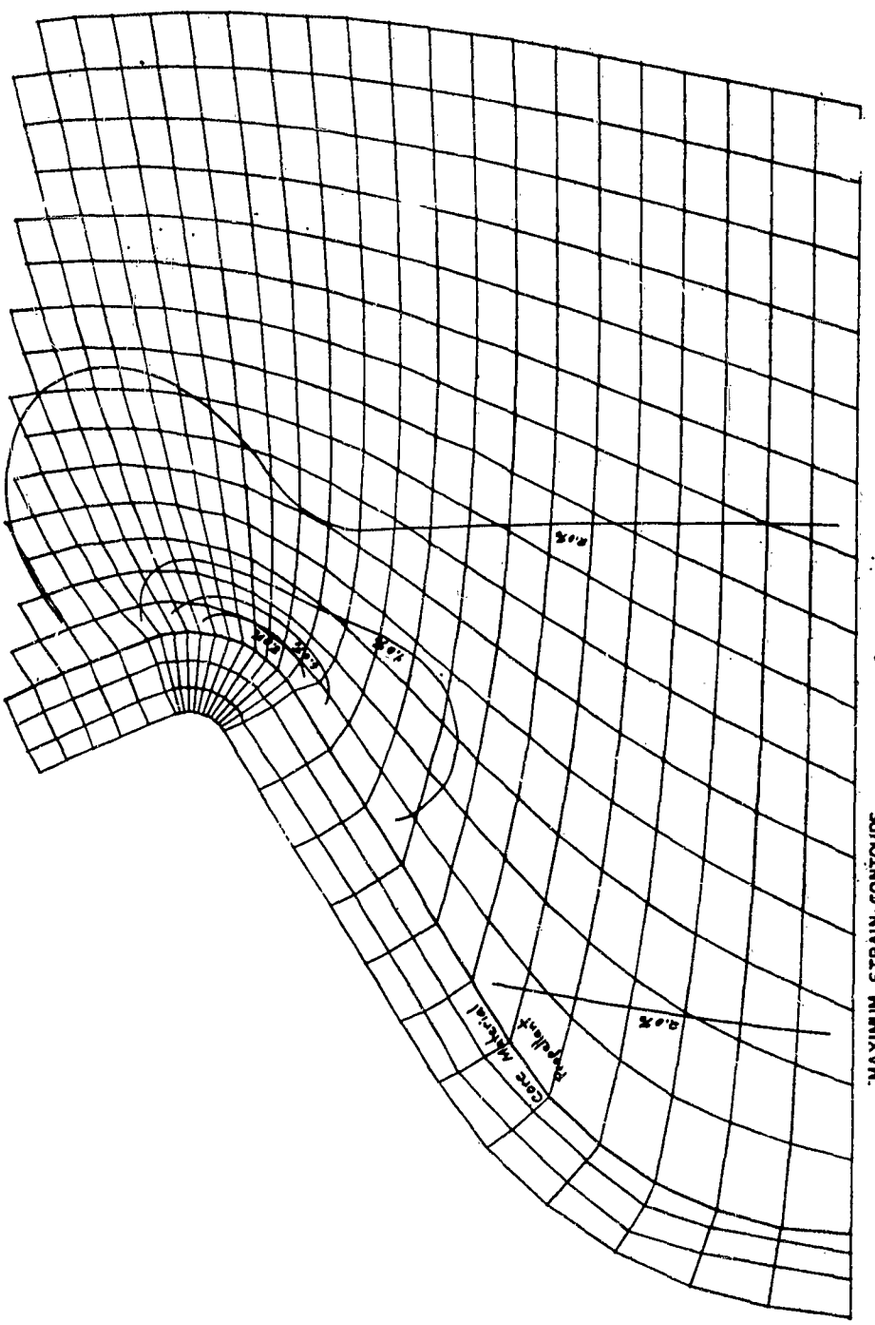


Figure C-2. Enlarged View of Area Enclosed by Dashed Line on Figure C-1.

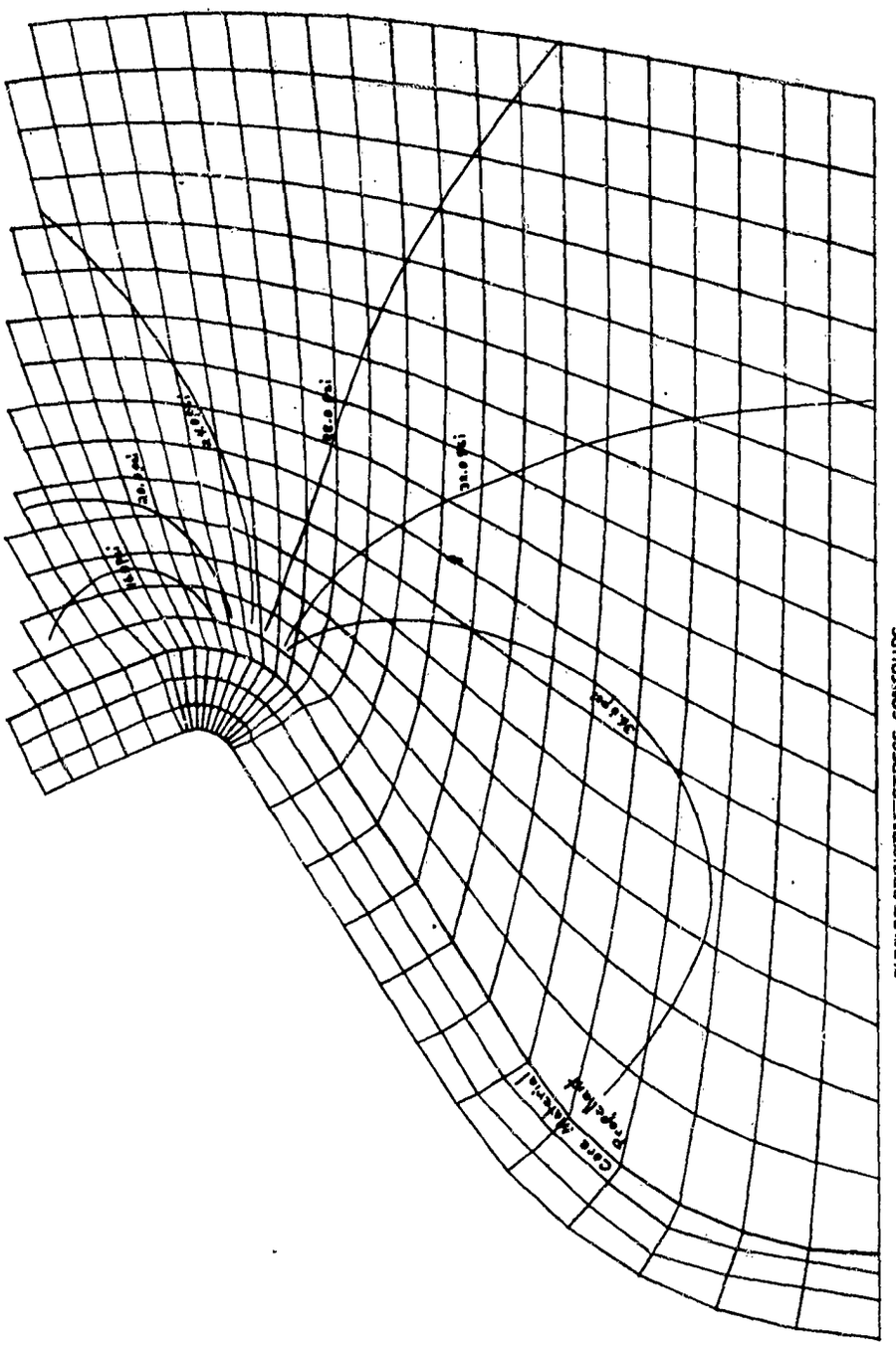


Figure C-3. Enlarged View of Area Enclosed by Dashed Line on Figure C-1.

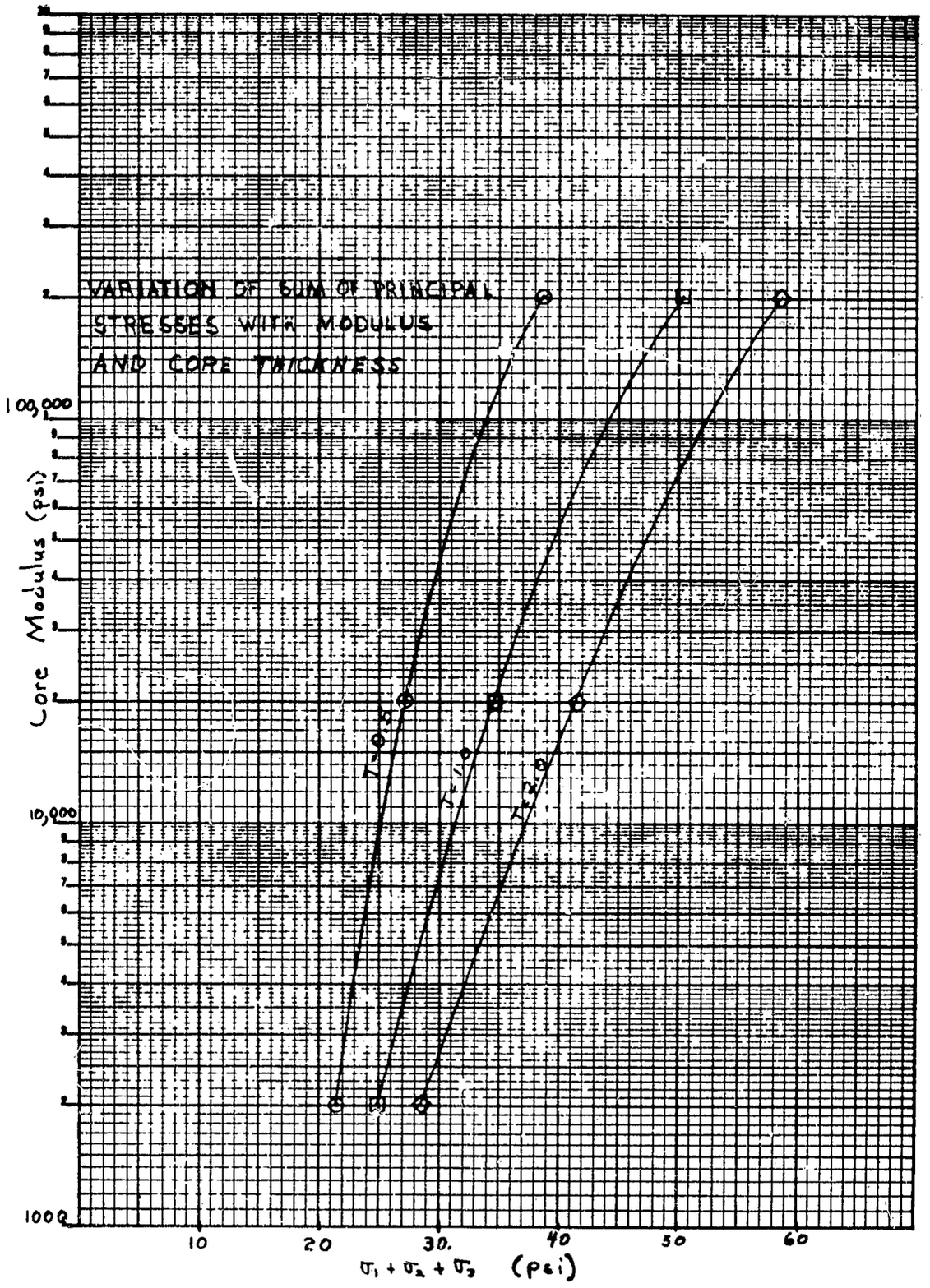


Figure C-4. Variation of Sum of Principal Stresses with Modulus and Core Thickness.

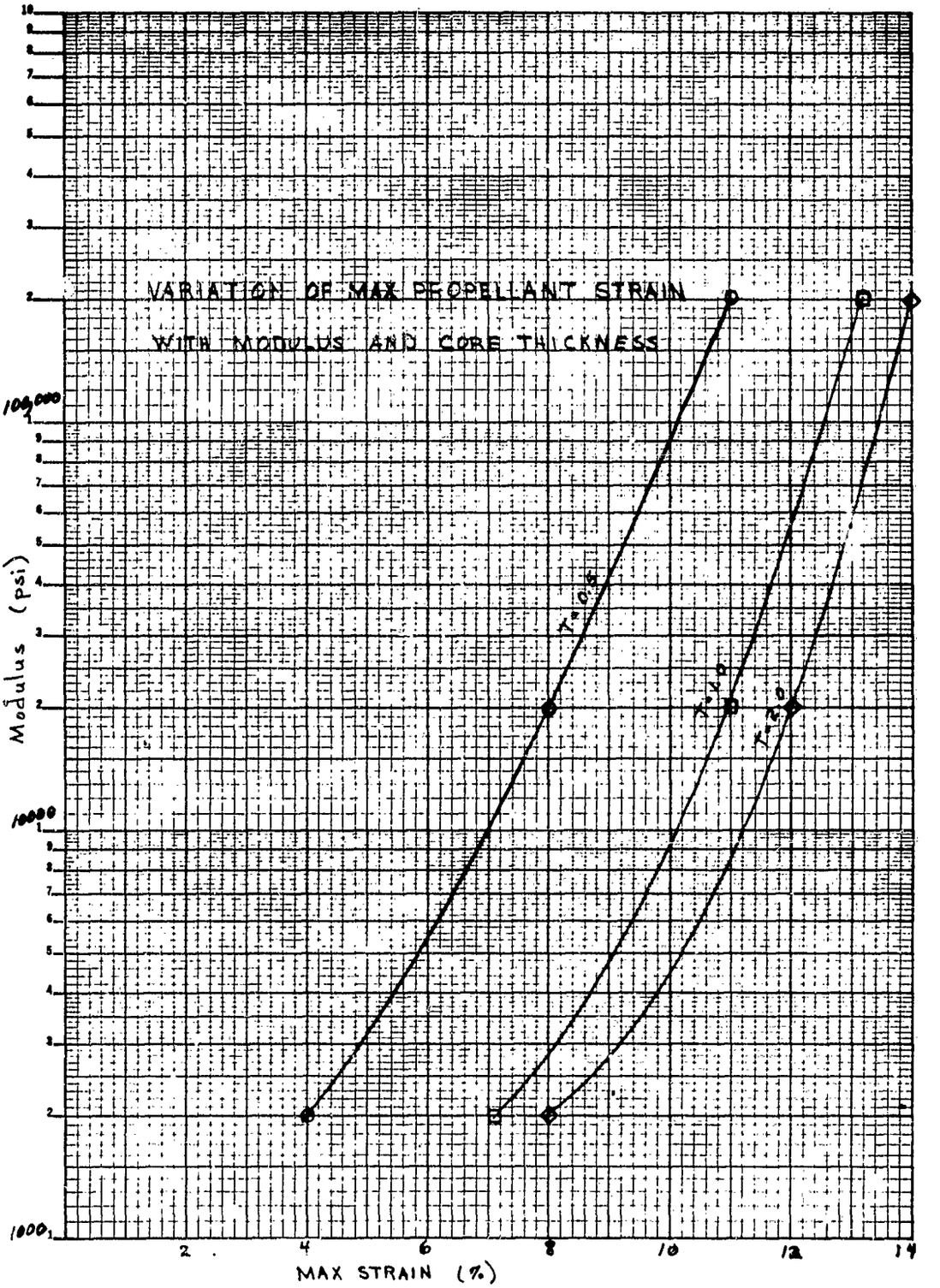


Figure C-5. Variation of Maximum Propellant Strain with Modulus and Core Thickness.

APPENDIX D

BUREAU OF EXPLOSIVES

ASSOCIATION OF AMERICAN RAILROADS

REPORT FROM CHEMICAL LABORATORY

T. C. GEORGE, DIRECTOR AND CHIEF INSPECTOR
WILLIAM G. McKENNA, CHIEF CHEMIST

FILE NUMBER 25-15-145
LABORATORY NUMBER 59021

EDISON, N. J., May 4, 1966

Propellant Explosives (Solid) Class B

IIT Research Institute

A sample of material identified as Rocket Propellant was received from IIT Research Institute of Chicago, Illinois.

The material is a buff colored solid. Two forms of the material were received. One was an annulus about 6" outside diameter, 4 1/2" inside diameter and 3/4 " thick. The other form was shavings of the product.

The composition is given as:	%
Ammonium Perchlorate	56
Cotton gauze	12
Resins	31

A #8 electric blasting cap was taped perpendicularly against the outside of one of the rings. When the cap was fired, the ring broke in two but did not explode or take fire.

Another ring was placed in a fire and burned without explosion. When the shavings of the product are ignited, they burn rapidly.

The mixture is stable when maintained at 75°C for 48 hours.

When tested in The Bureau of Explosives Impact Tester under a drop of 10" there is some decomppsition of the material but no explosions.

Material represented by this sample is described as Propellant Explosives (Solid) Class B and classed as Class B Explosive under the ICC Regulations.

Dr. W. G. McKenna
Chief Inspector

(AK)

RECEIVED
MAY 13 1966

APPENDIX E

CLOSED BOMB ENERGY EVALUATIONS

Energy calculations were based on closed bomb experiments with combustible core materials. Maximum pressures for various charge weights were fitted to the classic Neuman-Abel equation, Equation 1, to determine the product, nRT.

$$P\ (V-\eta) = nRT \tag{1}$$

where:

P is pressure, psi

V is volume per charge weight, $in^3/lb\text{-}in$

η is co-volume, $in^3/lb\text{-}in$

n is 1/molecular weight, g mole/g

R is universal gas constant

T is flame temperature, °K

The ratio of specific heat, γ, was determined by chemical-reaction calculation to be 1.29. Equations (2) and (3) were used to obtain specific impulse (I_{sp}), characteristic gas coefficient ($C^* = I_{sp}g/C_f$), exhaust velocity (V_e), and gas discharge coefficient (C_f) from the experimental product nRT and the calculated value of γ. Optimum expansion was assumed.

$$I_{sp} = \sqrt{nRT}\left(\frac{2\gamma}{\gamma-1}\right)^{1/2}\left[1-\left(\frac{P_a}{P_c}\right)^{(\gamma-1)/\gamma}\right]^{1/2} \tag{2}$$

$$C_f = \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma-1}\right)^{(\gamma-1)/(\gamma-1)}\left[1-\left(\frac{P_a}{P_c}\right)^{(\gamma-1)/\gamma}\right]^{1/2}} \tag{3}$$

where:

P_a is atmospheric pressure, 15 psi

P_c is chamber pressure, 1,000 psi

V_e is $I_{sp}g$

g is 32.2 ft/sec^2

APPENDIX F

CORE FORMING SYSTEM EVALUATION

By J. L. Murphy, Jr. 3 March 1966

The purpose of this paper is to define by amplification and clarification, where necessary, the comparison elements by which four major systems (plus two combination systems) of forming the grain configuration of very large solid propellant rocket motors will be evaluated. This discussion will follow the outline of Table XXXVIII. Rating weights weights have been assigned to each element and sub-element on the basis of a total of one thousand. In some extreme cases an element may have been assigned a negative rating weight.

I. COST

These will be costs of materials, processing steps, etc., either estimated or where possible obtained from actual experience or quotations. They will be used as a means of applying a rating factor to each of the several systems so that a value may be obtained which is additive to rating elements upon which a dollar value cannot be placed, such as safety, for example. See additional discussion on costs at the end of this paper.

A. Mandrel

This item is to include cost directly associated with the procurement of a mandrel system up through acceptance inspection. The items selected here are those which will vary in cost as a function of the mandrel system. Obviously, other costs are associated with the procurement of a mandrel, such as design, but because of the degree of accuracy with which these costs can be estimated at this time, they are assumed to be equal for each system. A figure is also shown for reusable costs. This is that cost of a mandrel system which represents a single investment and can be applied to subsequent motors.

B. Motor Processing Effects

Again, only processing steps have been included here which are functions of the mandrel system. Processing steps in the manufacture of a motor which are not affected by the type of mandrel used have not been included because they are equal for each system. For example, propellant raw material preparation and mixing costs will be equal for each system regardless of the type of mandrel used.

C. Special Tooling or Accessories

These items are believed to be self-explanatory and are again only those pieces of tooling equipment or accessories which will vary from mandrel system to mandrel system.

II. STATE-OF-THE-ART (At End of Phase I)

This section of the system evaluation table, which could be called technical feasibility or any one of several other names, is conceived as being an overall engineering evaluation of the present state-of-the-art of each mandrel system based solely on engineering data available at the end of Phase I plus estimates of the magnitude of the problem required to successfully reduce each system to practice in full-scale motors.

A. Present Feasibility of Concept

This is to be almost a simple "yes" or "no" comparison of whether or not the use of a particular system is possible and practical.

B. Degree of Reduction to Practice

This is an evaluation of the amount of development work done to date on a particular system. Rating factors will be assigned on the basis of the extent of the characterization of any materials or processes required for proper control of the manufacture and use of a particular system as well as on the actual size of motors in which each system has been used.

C. Major Problems to Reduce to Practice

Obviously, the collapsible mandrel system scores high on any state-of-the-art comparison at this time, since it has actually been built and successfully used to manufacture a 156-inch diameter motor. This item here will be a rating comparison based on major problems to be overcome in the other systems in order to bring it up to a comparable level with the collapsible mandrel system.

D. Estimated Costs to Solve Problems in "C"

Dollar values will be assigned here which will consist of budgetary estimates of the magnitude of a program necessary to bring an alternate mandrel system up to the present state-of-the-art of the collapsible mandrel system. These figures will be broad estimates only, since no detailed program plans as such will have been prepared for these programs. These costs will again be used to assign additive rating factors to the various systems. (Again, see additional discussion on costs at end of paper.)

III. USE

Rating factors under this category will be assigned as far as possible on the basis of actual available data, but in many cases they will be based mainly on engineering judgment. Although dollar values cannot be assigned to these items, nevertheless, this is one of the very important categories of system evaluation.

A. Safety

Factors to be considered here are to include not only those based on the characteristics of materials of construction employed but on several factors involved in manufacturing, transporting and using the mandrel.

B. Reuse

In rating this factor, the cost figure of reusable materials shown under Item I.A.1.c. is to be considered plus other factors which might be associated with motor-to-motor reuse of a mandrel system, such as storage requirements for filler materials in a membrane or combination system, between motor storage of explosive materials for fragmentating a frangible system and other factors. This item to some extent is repetitive here since, in addition to the cost figure mentioned above, it has also weighed to some extent in other items, such as between use maintenance and some under special tooling or accessories. However, this factor is considered important and the repetition is considered justified.

C. Reliability

This factor is to be an estimate of the reliability of such factors among various mandrel systems as the ability to produce acceptable mandrels from motor-to-motor with a minimum of rejects, the ability of the mandrel system itself to produce the proper core configuration in the finished motor, the probability that damage to the propellant grain might result during use of a particular system.

D. Ballistic Effects

This is to be an evaluation of the feasibility that the employment of a particular mandrel system might affect the ballistic properties of the finished motor, either favorably or unfavorably.

E. Vacuum Casting

In most instances vacuum casting is the desirable way to manufacture any solid propellant rocket motor. This comparison element therefore is to be rated on the ability of a mandrel system to be used under vacuum casting conditions.

F. Inspection

Factors to be weighed here will include the degree of insurance with which the mandrel can be inspected prior to use for dimensional accuracy, structural reliability after assembly in the motor, degree of surveillance which can be maintained during the casting operation, inspection of the grain surface after cure, and measurement of the thrust alignment of the motor after finishing and final assembly.

G. Grain Design Changes

A desirable feature to have in any solid propellant rocket motor is the ability to modify the grain design as system requirements change or as ballistic tests indicate with a minimum of cost. The various systems will be compared here on their ability to meet this requirement.

H. Weights

Rating factors will be assigned under this category based on weights involved among the various systems, for such items as whether the maximum unit weight required to be handled necessitates additional capital equipment investment, whether it affects transportation costs of the loaded motor and other factors.

I. Motor Cool-Down

In the manufacturing process of any solid propellant rocket motor using a conventional metal mandrel, a cool-down period of varying length must be allowed between the end of propellant cure and extraction of the mandrel. The elimination of the necessity of this step in the processing could be advantageous to the overall cost of the program. If a mandrel is to be left in-place until motor ignition, a deliverate cool-down period is no longer required. It is, of course, desirable to control motor cool-down to whatever extent is necessary to prevent damaging thermal stresses in the motor. However, in the case of a left-in-place mandrel, there would be no need to delay operation such as final finishing, nozzle installation and the like until this step had been completed.

IV. MOTOR STORAGE

Although no reported difficulties have been encountered in the industry with propellant slump in large space boosters, it is conceivable that future propellant which are desirable from other standpoints might produce this problem, in which case the grain support that could be obtained from a left-in-place mandrel would be highly advantageous. The various mandrel systems will be compared here on that basis including the probable compatibility of mandrel materials with the propellant or other items in the motor as well as a system's effect on the ability to inspect a motor internally just prior to launch or at various periods during long or short-term storage.

V. LAUNCH SITE EFFECTS

In this category the various mandrel systems will be compared on their probable effects on missile launching operations. Such possibilities will be considered as that of damage to the pad or other launch equipment from fragments from a combustible or frangible core system, leaking filler material from a membrane or combination system and the trouble and cost of either disposing of a filler material or of collecting it and returning it to the manufacturing site.

ADDITIONAL DISCUSSION ON COSTS

As pointed out above, what actual dollar values have been placed on the many items in the evaluation table were used as a basis for assigning rating factors to those comparison elements in order that they would be additive to rating elements to which a dollar value could not be placed. When this evaluation has been completed, the overall cost of the several systems will be calculated. These will include not only the cost for manufacturing the mandrel system itself, but the cost related to its use in manufacturing the large motor and related costs in the use of the completed motor. Such costs may then be used to compare the systems on a length of pay-out or other basis. Thus, if a system might not be as desirable from a technical standpoint as another, still some advantage for the system might be demonstrated over a production of a number of motors.

APPENDIX G

COST ESTIMATES OF VARIOUS CONCEPTS

APPENDIX G

COST ESTIMATES OF VARIOUS CONCEPTS

Cost estimates for the following concepts are included herein:

1. Collapsible Core
2. Membrane Core
3. Frangible Core
4. Laminated Combustible Core
5. Castable Combustible Core

The following labor rates, which include wages and overhead, were used for all concepts:

$15.00 Exempt

$ 8.00 Non-Exempt

Cost of reusable items appear only once in the cost of 10 motors.

I. COLLAPSIBLE CORE - COST ESTIMATE

		1 Motor	10 Motors
A.	Mandrel		
	1. Materials		
	Other than Filler Fluid	$ 5,048	$ 50,480
	Filler Fluid	- -	- -
	Reusable	383,500	383,500
	2. Fabrication	248,000	248,000
	3. Transportation to Loading Plant	1,800	1,800
	4. Acceptance Inspection (included in 2 above)		
B.	Motor Processing Effects		
	1. Core Checkout	20,705*	67,289
	2. Core Preparation	5,264**	5,264
	3. Core Installation	10,333	103,330
	4. Cleaning and storage (Incl. ins.)	- -	- -
	5. Between-use Maintenance	21,000	210,000
	6. Core Removal (Included in 5)	- -	- -
C.	Special Tooling or Accessories		
	1. Retracting Platforms	58,500	58,500
	2. Spindles	77,000	77,000
	TOTALS	$831,150	$1,205,163

* Use only 25% of this amount for motors 2 through 10

** Inhibiting of core (once only)

II. MEMBRANE CORE - COST ESTIMATE

	1 Motor	10 Motors
A. Mandrel		
1. Material		
Fabrication of Rubber Boot	$ 1,000	$10,000
For Membrane	800	8,000
For Reusable Tooling Items	58,608	58,608
Filler Fluid (Delivered)	94,967	94,967
Other Direct Purchased Items (Reusable)	6,763	6,763
Operating Supplies	1,000	10,000
2. Fabrication		
Reusable Items	32,412	32,412
Non-Reusable Items	5,000	50,000
3. Installation and Removal		
Assemble for Casting	9,632	96,320
Monitor during Casting and Cure	8,688	86,880
Remove and Prepare for Shipment	4,512	45,120
Removal and Recovery of Remaining Items at Launch Site	4,512	45,120
B. Motor Processing		
1. Mandrel Checkout	20,705	67,289*
2. Mandrel Preparation (included in fabrication)		
3. Mandrel Installation (included in fabrication)		
4. Cleaning and Storage	752	7,520
5. Between-Use Maintenance	752	7,520
6. Backhauling of Filler Fluid	2,000	20,000
C. Special Tooling and Accessories		
1. Filler Fluid Mixing, Conditioning, Handling and Monitoring System	61,280	61,280
2. Jigs for Sealing Film	16,420	16,420
3. Mould for Rubber Boot	8,824	8,824
TOTAL (10 Motors)		$733,043

*$20,705 + (5,176 x 9) Check out of first core estimated to be four times greater than subsequent core.

III. FRANGIBLE CORE - COST ESTIMATE

Item	1 Motor	10 Motors
A. Mandrel Materials		
1. Foam Materials	$14,786	$147,860
Mold Release (MR-22)	70	700
Solvent for Cleaning	171	1,710
Adhesive for Sealing	903	9,030
Explosive Components	72	720
2. Fabrication		
Foaming Sections	1,692	16,920
Patching and Trimming	512	5,120
Inspection (in process)	256	2,560
Explosives - "Bundles" and Harness	248	2,480
3. Transportation (on site)	N/A	N/A
4. Acceptance Inspection	316	3,160
B. Motor Processing Effects		
1. Core Checkout	N/A	N/A
2. Core Preparation (MR-22 Mold Release)	316	3,160
3. Core Installation		
Drum Installation and Alignment	632	6,320
Core Assembly	3,160	31,600
Explosives Final Assembly	94	940
4. Remove, Clean and Store Core Positioning Drum	632	6,320
5. Between Use Maintenance	N/A	N/A
C. Special Tooling and Accessories		
1. Retracting Platform	N/A	N/A
2. Spindles	N/A	N/A
3. Transportation Seals	N/A	N/A
4. Foam Machine	10,000	10,000
5. Molds (2 for straight sections, 1 for forward end)	6,500	6,500
6. Core Positioning Drum (complete with mold release "O" rings and accessories)	50,015	50,015
7. Holding Straps and Misc. Tooling (Expendable)	1,000	10,000
TOTAL	$91,375	$315,115

IV. LAMINATED CORE (IITRI) - COST ESTIMATE

	1 Motor	10 Motors
A. Mandrel		
1. Material	$ 38,900	$ 389,000
(Adhesive)	600	6,000
2. Fabrication (of sections)	41,456	414,560
3. Included in 2 above		
B. Motor Processing		
1. Core Checkout	N/A	N/A
2. Core Preparation	N/A	N/A
3. Core Installation		
Drum Installation and Alignment	632	6,320
Core Section Assembly	2,350	23,500
4. Remove, Clean and Store Drum	632	6,320
5. Between - use maintenance	N/A	N/A
6. Final Acceptance Inspection	316	3,160
C. Special Tooling or Accessories		
1. Retracting Platform	N/A	N/A
2. Spindles	N/A	N/A
3. Transportation Seals	N/A	N/A
4. Pre-preg Machine	107,000	107,000
Wrapping Machine	53,000	53,000
5. Mandrels (2)	10,000	10,000
6. Assembly Jig and Fixtures	10,000	10,000
Cure Racks, Dollies & Lowering Cage	15,000	15,000
7. Milling Machine	25,000	25,000
8. Ovens (2)	22,000	22,000
D. Buildings		
1. Wrapping	108,000	108,000
2. Milling	48,000	48,000
TOTALS	$482,886	$1,246,860

* IITRI design costs prorated

V. CASTABLE COMBUSTIBLE CORE - COST ESTIMATE

		1 Motor	10 Motors
A.	Mandrel	$ 27,880	$ 278,800
	1. Material	27,880	278,880
	(Adhesive)	160	1,600
	(Teflon) prorated	60	600
	2. Fabrication	21,742	217,420
B.	Motor Processing Effects	3,930	39,300
C.	Tooling	87,000	87,000
	TOTALS	$140,772	$624,720

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DOCUMENT CONTROL DATA - R&D
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author)
Thiokol Chemical Corporation
Huntsville Division, Huntsville, Alabama

2a REPORT SECURITY CLASSIFICATION
--

2b GROUP
--

3 REPORT TITLE
Development of a Manufacturing Process and Associated Equipment to Improve Internal Core Forming in Solid Propellant Rocket Motors

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Technical Report; 15 July 1965 to 1 June 1968

5 AUTHOR(S) (Last name, first name, initial)
Gualillo, S. P., and Dale, W. I., Jr.

6 REPORT DATE	7a TOTAL NO. OF PAGES	7b. NO OF REFS
May 1968	305	--

8a CONTRACT OR GRANT NO	9a ORIGINATOR'S REPORT NUMBER(S)
AF33(615)-2998 & Mods.	AFML-TR-68-114
b PROJECT NO S/A 1, 2, & 3 8-260	
c	9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d	Thiokol Control No. U-68-10B

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11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY
--	Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

13 ABSTRACT

Thiokol's program to investigate and evaluate techniques for forming the internal cavities in large solid propellant rocket motors was divided into three phases. Under Phase I, candidate processing techniques were evaluated and recommendations made for the technique which should be further developed in subsequent phases. At the conclusion of Phase I, the Air Force redirected effort on the program toward development of the castable combustible core concept as applied to the WS-120A system. During Phases II and III, the most promising combustible material was tailored and its suitability was demonstrated by static testing in 5-inch-diameter rocket motors. The combustible core concept could be used most effectively in applications where the propellant configuration prohibits removal of the core and with propellant configurations that are not already limited by propellant mechanical strain. The castable combustible core materials that were studied are representative of a broad family of rigid combustible materials. These materials can be tailored to have wide ranges of physical and ballistic properties by simple variations in ingredients. Consequently, they should be considered for use in any application where rigid combustible materials are required. The castable, combustible core material that was developed has a burning rate coefficient of pressure that is nearly zero. Consequently, materials of this type should be considered for any application in which minimum pressure sensitivity of burning rate is of prime importance.

DD FORM 1 JAN 64 1473

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Combustible core						
Membrane core						
Laminated combustible core						
Combustible material						
Rigid combustible materials						
Internal cavities						
Casting fixtures						
Solid propellant rocket motors						
Burning rate exponent						

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